PB86-183936

Wet Oxidation of Municipal Sludge by the Vertical Tube Reactor

Applied Science and Engineering, Inc.
Englewood, CO

Prepared for

Environmental Protection Agency, Cincinnati, OH

Apr 86

U.S. Department of Commerce
National Technical Information Service
NTIS

PB86-183936

EPA/600/2-86/043
April 1986

WET OXIDATION OF MUNICIPAL SLUDGE BY THE VERTICAL TUBE REACTOR

by

Jay L. McGrew
George L. Hartmann
Christina B. Cassetti
John E. Barnes
William G. Purdy, Editor

Applied Science and Engineering, Inc.
Englewood, Colorado

Contract No. 68-03-2812

Project Officer

Atal E. Eralp

Wastewater Research Division
Water Engineering Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, OH 45268

WATER ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OH 45268

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/2-86/043	2.	3. RECIPIENT'S ACCESSION NO. PB86 183936/AS
4. TITLE AND SUBTITLE Wet Oxidation of Municipal Sludge by the Vertical Tube Reactor		5. REPORT DATE April 1986 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Jay L. McGraw, George L. Hartmann, Christina B.Cassetti, John E. Barnes, and William G. Purdy		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Applied Science and Engineering, Inc. 3244 South Platte River Drive Englewood, Colorado 80110		10. PROGRAM ELEMENT NO. CAZB1B 11. CONTRACT/GRANT NO. Contract No. 68-03-2812
12. SPONSORING AGENCY NAME AND ADDRESS Water Engineering Research Laboratory, Cin., OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final Project Report 14. SPONSORING AGENCY CODE EPA/600/14
15. SUPPLEMENTARY NOTES Project Officer: Atal E. Eralp (513) 684- 2621		

16. ABSTRACT

A study was undertaken to assess the feasibility of carrying out oxidation of dilute sewage sludge by means of the vertical tube reactor (VTR) system. A pilot scale facility along with a laboratory reactor were used for this study. Dilute sewage sludge was oxidized in the laboratory reactor at temperatures up to 343 °C with approximately 80% COD reduction, and to 265 °C in the pilot scale reactor with approximately 50% COD reduction.

The pilot scale study provided information on scale buildup and control, structural, and mechanical design, metallurgy, hydrodynamic behavior, heat transfer, and other significant engineering factors. The results of this program indicate that the VTR process potentially has technical and economic viability as a means of treating sewage sludge in certain cases and that a full scale demonstration is warranted.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 133
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

DISCLAIMER

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under Contract No. 68-03-2812 to Applied Science and Engineering, Inc. It has been subject to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendqtion for use.

FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxics Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

The objectives of this study were to demonstrate the feasibility of oxidizing municipal wastewater sludges in a deep well under hydrostatic pressure using pilot scale facilities at Englewood, Colorado, and to develop design data for the construction of full scale demonstration facilities.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

The Vertical Tube Reactor System (VTR) is designed to oxidize high strength liquid organic wastes using wet combustion principles. The reactor vessel used can be envisioned as a very long U-tube where the waste to be oxidized flows down one leg (downcomer) and returns through the other leg (upcomer). The downcomer has provision for air injection to support combustion and the upcomer is surrounded by a heat exchange jacket which provides the thermal energy necessary to initiate and maintain temperatures appropriate for the oxidation reactions.

The VTR is made up of stainless steel concentric tubes suspended in a well, a configuration that uses little space compared to above-ground wet oxidation vessels. The counterflow configuration promotes efficient heat exchange and the pressurization afforded by the weight of the liquid in the tubes is acquired safely and economically.

A pilot-scale VTR system consisting of a 1,500 foot by two inch diameter reactor, was operated in this program over a period of time utilizing municipal sludge to accumulate engineering data and operating experience. The information obtained was compared with oxidation data obtained from an existing laboratory bench reactor. Correlation between pilot plant and bench reactor data over the range of conditions afforded by the pilot-scale system was sufficiently reliable to allow the laboratory reactor to be used to obtain reaction data over ranges of operating conditions approximating full-scale.

The pilot-scale system achieved chemical oxygen demand (COD) removals of up to 50% while the laboratory reactor tests utilizing municipal sludge from several sources and simulating deeper reactors with consequent higher temperatures and pressures, obtained COD removals of up to 80%.

Theoretical predictions of reactor fluid flows, pressure, and heat transfer showed reasonable correlation with pilot plant operating results.

The pilot-scale test program provided information on structural, mechanical and other operational problems important to the design of full-scale systems.

Calcium carbonate scale buildup on reactor surfaces was experienced but was removed with a nitric acid flush.

A metallurgical inspection at the completion of the program of the surfaces of the 304-L stainless steel tubes used in the reactor showed no stress cracking norcorrosion in the parent metal. Some stress cracks and corrosion pitting were noted in non-annealed, weld-affected areas, but none was found in annealed weld areas.

Some difficulty was experienced with leaks at pipe joints in the reactor. These threaded joints may need to be replaced with welded joints in full-scale applications.

Analysis of metals in the reacted liquid and settled solids indicates that the metals tend to remain with the settled solids, but the poorly understood interacting effects of metal solubility, adsorption, and desorption have prevented a definitive explanation of the fate of metals in the VTR.

No odors were perceived either at the pilot plant or with the laboratory reactor. Chemical analysis of liquid samples taken from the pilot plant confirms the absence of odor-causing low molecular weight volatile organic compounds.

In summary, the VTR is a potential treatment process for stabilization of organic wastes when significant sludge volume reduction is required, where stringent requirements for sludge disposal exist, when destruction of toxics or pathogenic organisms is necessary and/or where potential energy recovery from high strength wastes is good. A major goal remaining is to demonstrate VTR steady-state operation at full-scale. This experience will not only produce operational information and characterize certain process variables, but will better define actual operating costs for wastes of various strengths.

CONTENTS

Foreword iii
Abstract iv
Figures. ix
Tables xi

1. The Vertical Tube Reactor Process 1
   Introduction 1
   Wet Combustion Theory 1
   Conventional Applications. 3
   Design Concept 4
   Operation Concept. 5
   Design Features. 6
2. The Pilot Plant Reactor (PPR) Test Program. . 9
   Introduction 9
   PPR Design Criteria. 9
   PPR Description. 10
   Test Program Objects 10
   Test Operations. 11
      Test Period 1 11
      Test Period 2 12
      Test Period 3 13
      Test Period 4 13
   Operating Problems 14
      Process Control 14
      Reactor Design. 15
3. LBR Test Program. 17
   LBR Description. 17
   LBR Operation. 17
   LBR Scale Research 20
      Oxidation Characteristics of Sludges 20
      Correlation Between LBR and PPR COD Reduction Data. 34
      Reductions and Data from Chemical Analysis. 34
4. Computer Simulation of the Vertical Tube Reactor Process 44
   The Hydrodynamic Model 44
   The Heat Lost to Effluent Model. 46
   The Heat Lost to Surrounding Earth Model. 46
   Correlation of Computer Models with Pilot Plant Data 47

5. Full Scale Design 51
Design Goals 51
Full Scale Plant Description 51
Energy Balance of Full Scale Model . . . 52
Capital Costs, and Operations and Maintenance Costs of Full Scale Plant. . . . 55
References 59
Appendices 61

A. The PPR Facility. 61
B. Description of Wastewater Treatment Plant Facilities. 68
C. LBR Generated Data. 71
D. PPR Generated Data. 95
E. Pilot Plant - Computer Model Correlation Data. 114

FIGURES

Number		Page
1	Typical VTR profile	6
2	Typical VTR cross section	7
3	Temperature vs. retention time for a typical VTR.	7
4	Drawing of the Laboratory Batch Reactor	18
5	Temperature vs. time profiles for VTR and LBR runs	19
6	LBR COD RDXN data for 30 minute reaction times for sludges at five stages of treatment	23
7	LBR COD RDXN data for 60 minute reaction times for sludges at five stages of treatment	24
8	LBR COD RDXN data for digested sludge at 30 and 60 minute reaction times.	26
9	LBR COD RDXN data for blended sludge at 30 and 60 minute reaction times.	27
10	LBR COD RDXN data for primary sludge at 30 and 60 minute reaction times.	28
11	LBR COD RDXN data for primary with food processing waste at 30 and 60 minute RXN times . . .	29
12	LBR COD RDXN data for domestic waste at 30 and 60 minute reaction times.	30
13	LBR and PPR COD reduction data	36
14	LBR solids reduction data 60 minute reaction times	38
15	LBR solids reduction data thirty minute reaction times	39
16	Longmont VTR operation.	54

Number		Page
17	Heat flow to rock from VTR	56

TABLES

Number		Page
1	The Source of Each Sludge and its Stage of Treatment	21
2	Comparison of COD RDXN Data for Sludges at Five Stages of Treatment	22
3	Comparison of Percent SCOD/TCOD in the Effluent	31
4	Comparison of Percent TBOD/TCOD in the Effluent	32
5	Influent and Effluent pH Data for Runs on Sludges	33
6	COD Correlation Data Between PPR and LBR	35
7	Summary of LBR Solids RDXN Data.	37
8	Summary of PPR Solids RDXN Data.	37
9	PR Metal Concentration Data.	41
10	LBR Metal Concentration Data	42
11	PPR Off-gas Analysis	43
12	LBR Effluent Volatile Acids Data	43
13	Hydrodynamic Computer Model-Pilot Plant Correlation.	49
14	Heat Lost to Effluent Model-Pilot Plant Correlation.	50
15	Longmont Full Scale VTR Description.	53
16	Full Scale Plant Energy Balance.	57
17	Estimated Capital Costs, and Operation and Maintenance Costs for VTR Facilities	58

SECTION 1

THE VERTICAL TUBE REACTOR PROCESS

INTRODUCTION

The Vertical Tube Reactor (VTR) (U.S. Patent Number 4,272,383) developed by the Vertical Tube Reactor Corporation, a subsidiary of Applied Science & Engineering, Inc., (AS&E, Inc.) Englewood, Colorado, is designed to treat and dispose of municipal and industrial wastes by wet air oxidation (wet combustion). The products of this process are easily dewatered ash and a supernatant containing low molecular weight organics.

The VTR process is especially applicable to wastes which are difficult to dewater or which have sufficiently high organic content to maintain a thermally self-sustaining (autogenous) reaction.

Because it is not necessary to supply energy for the latent heat of vaporization (since oxidation must occur in the presence of a liquid) wet air oxidation is particularly applicable for materials like organic sludges which are combustible but cannot be separated readily from water and which can supply some or all of the heat required for reaction. While most combustion processes require dewatered sludge to achieve thermal self-sufficiency, considerably less concentration of the organic matter is adequate for wet combustion.

WET COMBUSTION THEORY

If sufficient air (oxygen), temperature, and pressure are present, any burnable substance can be oxidized in a liquid state. This wet combustion reaction proceeds exothermically and if organic content of the material is high enough and heat losses are controlled, thermally self-sufficient (autogenous) combustion can be achieved.

Wet combustion is the result of three types of chemical reactions. Initially, the destruction of solid organic waste is predominantly the result of heterogeneous (two-phase) oxidation due to direct contact and ensuing reaction between adsorbed oxygen gas and organic solids. At elevated temperatures these solids are quickly reduced to simpler organic

colloids which are then solubilized by hydrolysis. Hydrolysis splits the organic polymers from both colloidal and soluble organic matter into smaller units but will not destroy them. The only remaining path for ultimate destruction of the organic matter is liquid phase oxidation, i.e., wet combustion, following the individual collisions and interactions of dissolved oxygen with solute elements or compounds in solution.

In wet combustion, organic matter can be potentially stabilized to carbon dioxide and water. Organic nitrogen is converted to ammonia and sulfur to sulfates. One of the last residual compounds prior to complete oxidation is acetate.

Oxygen must be added to the wet combustion system in stoichiometric proportions at a rate that will not impede combustion. Oxygen in excess of stoichiometric requirements does not accelerate the process and is economically undesirable because of air compression costs. In practice, excess quantities of air above stoichiometric requirements may be necessary to account for differences between ideal and actual combustion conditions. The chemical oxygen demand (COD) of the influent material is normally used as a convenient parameter of oxygen requirements. It is roughly equal to the oxygen utilized in the combustion process. (Refer Page 43, Table 12).

As the waste is reacted with oxygen, heat is produced. Municipal waste has a heat of combustion of approximately 3300 Cal/gram (6,000 BTUs per pound of COD). So typical untreated municipal sludge with a COD of 10,000 mg per liter has an overall heating caloric value of approximately 33 Cal/gram. For reference, fuel oil has a combustion value of approximately 11,000 cal/gram. Thus sludge must be processed at very high overall thermodynamic efficiency if an autogenous process is to be achieved.

Pressure downhole in the VTR at any point is a function of the weight of the liquid above it. Maximum allowable temperature at any point is just below the boiling point of the liquid. Retention time is dependent on the depth and diameter of the VTR and the velocity of the mixture flowing through it.

With sufficient conditions of temperature and pressure, wet oxidation proceeds until the organic removal rate decreases to zero and percent organics removed remains constant. The organics remaining at this point are termed refractory organics. At low temperatures of 100^0C to 200^0C, this plateau or equilibrium is not reached for hours. Above 300^0C, it is reached in a matter of minutes. The rate of oxidation will increase up to

the critical point of water (374^{0}C). The height of the plateau also increases with increasing temperature. Thus, the extent and rate at which a material is oxidized is significantly influenced by reactor temperature with very little oxidation occurring below approximately 150^{0}C. Temperatures of 350^{0}C or more are required for 80% COD removal.

In summary, five important parameters control the performance of wet oxidation units: feed solids concentration, pressure, temperature,time and air supply. The COD test is normally used as a measure of process efficiency. The expected average wet oxidation efficiency for the VTR is 70-90 percent of COD reduction. Some organic matter in the form of low molecular weight compounds such as organic acids, aldehydes and acetates will be observed in the effluent. Final oxidation products are highly dependent on the degree of oxidation and the composition of the waste.

CONVENTIONAL APPLICATIONS

Conventional wet combustion technology involves pumping waste and air into a pressure tank, heating the mixture to the desired reaction temperature, and stirring to carry out the reaction. Generally, the hot reacted liquid and gas is circulated in counter-flow heat exchange with the cool unreacted fluids to permit heat recovery and consequent reduction of operating costs.

The need for high pressure tanks, pumps, and compressors results in high capital cost and expensive energy consuming operations. Municipal sludge is especially difficult to pump to high pressure because it tends to be a viscous liquid with considerable solid phase content, including hair and fine sand-like abrasive. Stringy and abrasive materials are especially detrimental to positive displacement pumps.

Corrosion resistant pressure vessel design, high pressure liquid pump technology, and heat exchanger state of development are such that wet oxidation of municipal sludge in conventional pressure tanks is technically feasible.

But maintenance and safety considerations, capital and operating costs, and the requisite high level of plant site technological skill needed for continuous operation are such that conventional "pressure tank" wet oxidation is not currently an economically feasible method of disposal of municipal waste.

DESIGN CONCEPT

Thermodynamically it is theoretically possible to reduce the operating energy requirements of a conventional wet oxidation system by use of an extensive heat exchange system, and in addition passing the effluent hot pressurized gas through a turbine which in turn is coupled to the air compressor. If the compression and decompression could thus be accomplished in a nearly adiabatic, isotropic, reversible manner, little net work of compression would be needed. Unfortunately, friction and slippage in real compressors and turbines make such a pressurization and depressurization impractical. Further, the important goal of simplifying the system for application to municipal sludge would be lost if elaborate compressors and turbines are used.

In the search for potentially feasible wet combustion concepts AS&E, Inc., formulated the following selection criteria.

1. the overall thermodynamic process is at least slightly exothermic;

2. the system must employ only conventional low pressure rotating machinery;

3. operation and maintenance can be accomplished by trained but moderate-skill-level personnel.

A concept which promised virtually complete satisfaction of these criteria was an extended, vertical U-tube to achieve reaction pressure, temperatures, mixing and reactant retention time. In the VTR this unique concept is expressed as two very long concentric tubes suspended in a conventionally cased deep well. The waste liquid and air are injected into the center tube (downcomer) at the earth's surface at low pressure. As the waste stream and air flow down the tube the mixture is heated by counterflow heat exchange with the upflowing oxidized fluid. As the downflowing waste approaches the bottom of the tube system the temperature and pressure become sufficiently high to initiate the oxidation reaction. The tube lengths and diameters are appropriately sized to allow an adequate retention time in the high temperature/pressure reaction zone in order to achieve a high degree of reaction completion.

The oxidized waste ultimately flows up the annulus between the two tubes (upcomer) and is cooled by the transfer of heat to the downflowing fluid. As the fluid ascends, the pressure also decreases due to decreasing hydrostatic head. Thus, the pressurization and depressurization of the fluid waste, and

heat exchange, are accomplished in an highly efficient nearly reversible thermodynamic process.

Oxygen needed for combustion is supplied by the injection of air into the downcomer at several depths typically ranging from 150 to 800 feet depending on influent COD. When waste oxygen demand (COD) exceeds air supply capability, the waste is diluted with effluent or other low COD strength wastes.

A heat exchange jacket surrounding the outer tube from a short distance below the wellhead to the bottom of the U-tube circulates a heat transfer fluid heated when necessary in a burner at the wellhead, to preheat the reactor and to add or extract heat as required to maintain appropriate temperatures during reactor operation. Insulation to minimize heat losses to the surrounding rock complete the basic VTR design. Schematic views of a typical full-scale reactor are shown in Figures 1 and 2.

OPERATION CONCEPT

In actual operation, as the waste stream and air flow down the tube, they undergo natural pressurization due to the hydrostatic head above. Thus fluid pumps need to be primarily designed to overcome surface friction and pressure head at their influent or injection point. They do not need to develop the high pressure actually experienced at the bottom of the reactor. At some depth (typically 1,500 to 2,000 feet) temperature of the waste fluid increases to 350^0F due to heat transfer from the upcomer effluent to the downcomer influent and wet combustion effectively begins. As the fluid flows through the reactor, oxidation proceeds until either the organic material or dissolved oxygen are depleted or until hydrostatic pressure and temperature decrease below those necessary to support combustion. Upflowing oxidized waste is gradually cooled as it transfers heat to the downflowing fresh waste.

A temperature profile for a typical reactor as a function of retention time is shown in Figure 3. Any excess heat which may result from the exothermic oxidation reactions is removed from the reaction zone by the heat exchange jacket. Excess heat can be available for use at the ground surface. Effluent temperature is expected to be within 5^0F of the influent temperature.

DESIGN FEATURES

The VTR has no moving parts below the ground surface and needs no high pressure equipment above ground like that required for conventional wet oxidation methods.

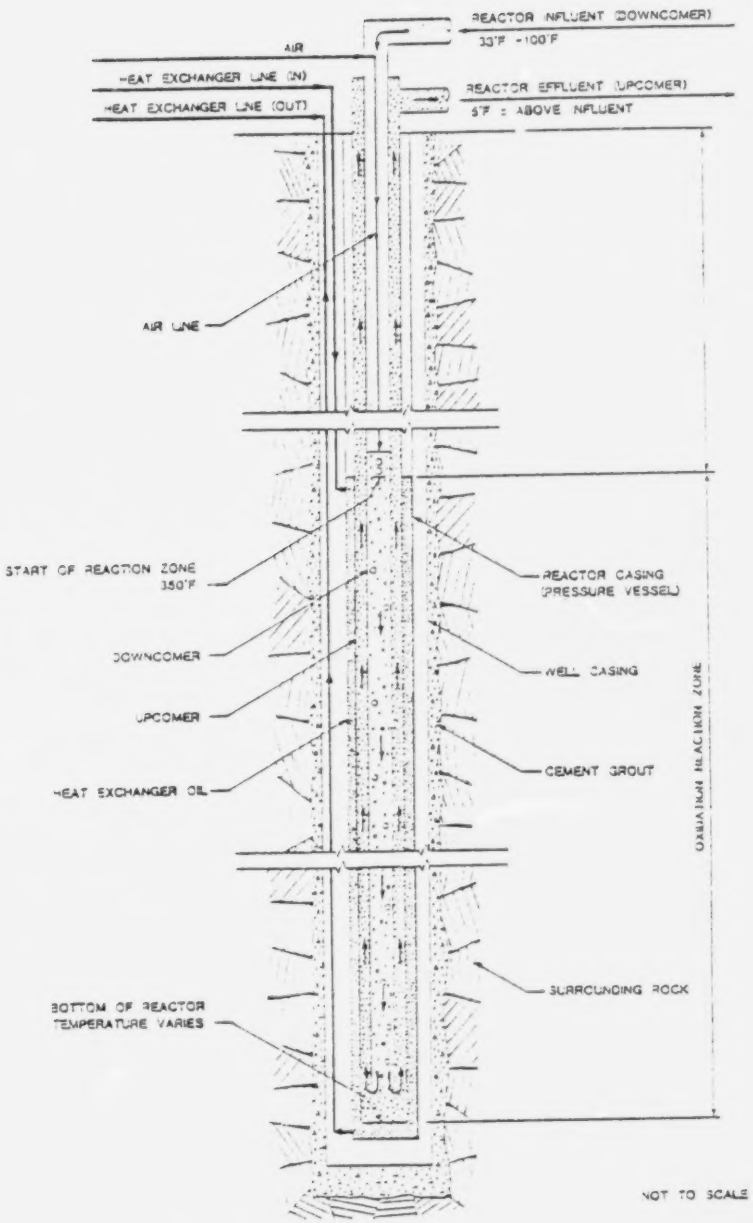

FIGURE 1. TYPICAL VTR PROFILE

Reproduced from
best available copy.

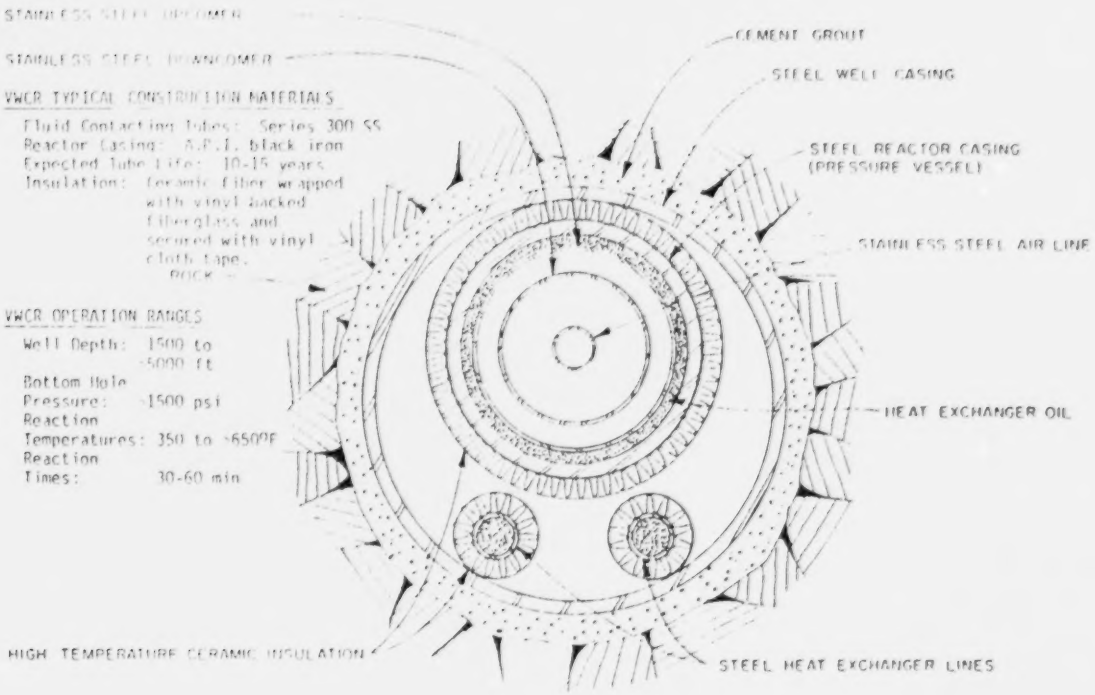
STAINLESS STEEL UPCOMER
STAINLESS STEEL DOWNCOMER
VWCR TYPICAL CONSTRUCTION MATERIALS
Fluid Contacting Tubes: Series 300 SS
Reactor Casing: A.P.I. black iron
Expected Tube Life: 10-15 years
Insulation: Ceramic fiber wrapped with vinyl backed fiberglass and secured with vinyl cloth tape.
Brick
VWCR OPERATION RANGES
Well Depth: 1500 to ~5000 ft
Bottom Hole Pressure: ~1500 psi
Reaction Temperatures: 350 to ~650°F
Reaction Times: 30-60 min
HIGH TEMPERATURE CERAMIC INSULATION
CEMENT GROUT
STEEL WELL CASING
STEEL REACTOR CASING (PRESSURE VESSEL)
STAINLESS STEEL AIR LINE
HEAT EXCHANGER OIL
STEEL HEAT EXCHANGER LINES

FIGURE 2. TYPICAL VTR CROSS SECTION

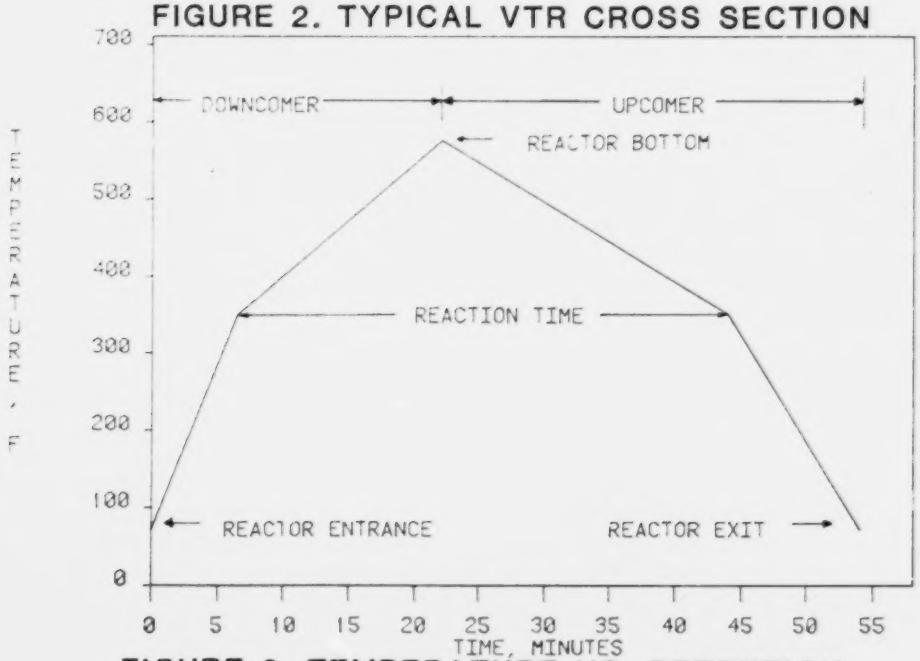

FIGURE 3. TEMPERATURE VS. RETENTION TIME FOR A TYPICAL VTR

The concentric U-tube arrangement of VTR affords very high heat recovery from the effluent to the influent waste stream. The entire reactor is in effect a counterflow heat exchanger, thus greatly reducing heat losses normally encountered in wet oxidation systems. In addition, as the surrounding earth approaches equilibrium with a continuously operating VTR, operations will be less affected by waste quality changes or above-ground (climate) influences because the surrounding earth will act as a thermal buffer.

The VTR requires little "real estate". At the same time its vertical configuration and its compactness make downhole accessibility difficult should temperature and pressure measuring devices or other well components need to be unplugged, inspected or replaced. Thus mechanical reliability and maintenance of the VTR system are of critical importance.

SECTION 2

THE PILOT PLANT REACTOR (PPR)

TEST PROGRAM

INTRODUCTION

On the strength of positive indications of the feasibility of the VTR scheme from initial analytical and laboratory research, and confirmation by early tests begun in 1973 with a bench-scale Laboratory Reactor (LBR), the next phase of the VTR development program, construction and operation of a pilot-scale reactor, was initiated in 1976 with private funding.

Operation of the Pilot Plant Reactor (PPR) on an intermittent basis during 1977-78 supported the earlier indications of VTR feasibility and led to the solicitation (1) and award (2) of the EPA contract covering the work summarized in this report.

PPR DESIGN CRITERIA

Laboratory work, including runs with the LBR, established essential (and analytically complex) relationships between sludge characterisitics, reaction temperatures, pressures and times, air supply and COD reduction. From this data base air/sludge ratios and flow rates, heat transfer parameters and well design characteristics were determined.

The PPR designed was large enough to provide essential concept verification and engineering data. Designed to process up to 8 gpm of municipal sludge with a COD of 2,000 mg/ℓ, the PPR would operate at a maximum downhole temperature of 500^{0}F at 1,000 foot depth, with a retention time of 20 to 30 minutes to accomplish up to 50% COD removal.

Modifications of the Pilot Plant during the program covered by this report increased the actual depth of the PPR to 1,500 feet and, with pressurized influent, the effective depth to 3,600 feet, with a maximum operating temperature of 575^{0}F.

PPR DESCRIPTION

The reactor of this project consisted of a 1-3/4 inch diameter downcomer in a two (2) inch diameter upcomer, both of 304L stainless steel and inserted in a 2-1/2 inch diameter reactor casing of schedule 40 API (American Petroleum Institute) pipe. The reactor, air line, heat exchanger lines, instrumentation and insulation were all suspended in a five (5) inch diameter standard API well casing. The PPR extended to a depth of 1,000 feet below the ground surface in a 9,000 foot deep abandoned oil well located 25 miles east of Denver, Colorado. (Refer Page 7).

A plan layout and pictorial description of the PPR surface facility is presented in Appendix A along with a summary of operating procedures. Schematic diagram of the process piping, control and instrumentation can be found in that Appendix also.

PPR instrumentation provided for the measurement of pressure by bourdon tube gauges, temperature by thermocouples, sludge flow rate by magnetic flow meter, dilutant flow rate by vane type flow meter, air flow rate by rotameter and dissolved oxygen measurement by an in-line DO meter. To provide maximum opportunity for control of the process, all data were taken by visual readout and manually recorded in a test log. A typical log sheet is shown in Appendix A.

TEST PROGRAM OBJECTIVES

The main objective of this study was to operate the system "on a continuous basis over an extended period of time to monitor, measure, analyze and otherwise evaluate all significant operating parameters and reaction information during operation." (2) At the same time the LBR was to be used to "produce a broad base of reaction data on a variety of different types of municipal sludge."(2)

The test program envisioned for the PPR at that time included seven continuous runs of at least 30 days duration subdivided into four tests series, each of different combinations of reaction temperature and time. After each series, the reactor was to be disassembled and inspected to determine whether or not corrosion, scaling, fouling or other deterioration had occurred. It was contemplated that those tests would be conducted over a period of fifteen months and accumulate approximately eight months run time.

In actuality that test schedule proved to be overly ambitious. Changes to the PPR caused by both operating problems and changes in test conditions resulted in total run time of 150 days including two continuous runs of 40 and 20 days over a

test period of 25 months. The following paragraphs summarize PPR operations during that period.

TEST OPERATIONS

From July, 1979, through late March, 1981, the PPR was operational during four periods, interspersed with down-time for repairs and incorporation of design changes. These test periods are summarized in the following paragraphs. For the most part the results obtained are included in Sections 3 and 4 of this report.

Test Period 1 (July-October 1979)

The reactor was started up and shut down several times in preparation for the first thirty day steady state testing period. Limited reactor COD testing was done at this time. The thirty day run was aborted during the first day because of power failure resulting in a two hour loss of power to the site. During this time metal solids in the heat exchanger settled at the bottom of the reactor. When power was restored these particles, of steel filing-like size, had consolidated to such a degree that heat exchanger flow was blocked, necessitating pulling the reactor.

The reactor was pulled during October and November, 1979, and the reactor heat exchanger line system was redesigned to elminate potential blockage problems in the future. Analysis of samples of the stainless steel upcomer and downcomer (8) showed local corrosion in the downcomer, caused, it is believed, by chlorides in the sludge in conjunction with scale formation on the downcomer wall.

In reassembling the reactor several topside changes were made to improve reactor controls. In fact throughout the study period minor changes in equipment controls and operating procedures were made to improve process performance and reliability. A summary of the more significant operating and design problems encountered and their actual or proposed resolution is presented later in this Section. The reactor was reinstalled in the first half of 1979, and by mid August the PPR was ready for steady state testing.

Sludge flow was measured by a magnetic flow meter, while dilutant (clear water) flow was measured by a conventional positive displacement integrating meter. Sludge in (reactor mixed liquid input), and out (reactor output) COD determinations was made in the laboratory on grab samples using the standard potassium dichromate titration technique.

The average COD reduction during these runs was approximately 12% but this determination is not believed to be valid for the particular temperatures and reaction times. The reasons for this are two fold. First, a large quantity of biological slimes was found growing in the reactor upcomer and it is believed to have biologically removed some of the COD. Secondly because of variation in sludge flows caused by non-uniform sludge concentration in the sludge tank the VTR effluent samples taken were not representative of the influent samples.

Two major problems were encountered with the reactor itself during these tests. One, low level steam leaks occurred in the reactor case screw joints. These joints were made using a high quality, copper filled, high temperature, joint sealing compound and precise tightening torque control, but after a few weeks of stop/start testing, seeps were incurred as evidenced by the loss of a small amount of heat exchanger water, and also by an observed effect on the downhole thermocouples which showed a tendency to a somewhat low and very erratic temperature reading. It was found that by occasionally placing a small amount of aluminum powder leak sealer in the system the loss of heat exchanger water ceased and the thermocouple reading rose and became steady with time. This problem demonstrated the need to seal the joints in full scale reactors by welding or other positive means.

The second problem, deposit buildup in the reactor, was evident when the reactor was removed and inspected.

Test Period 2 (July-September 1980)

The reactor was operated nearly continuously from August 22 to September 26, during which time the maximum reactor downhole temperature was in the 200^{0}C range. Because of numerous minor problems with topside equipment, more attention had to be given to plant maintenance during this period than to process control.

Output dissolved oxygen (D.O.) was generally fairly low indicating qualitatively a consumption of oxygen in the reactor. This series of tests clearly indicated that reactor output liquid D.O. measurement can reliably be used for process control.

Toward the end of the thirty day continuous run an increase in pressure drop through the reactor and an increase in temperature difference between influent and effluent signaled the presence of scale deposit. Flushing with dilute nitric acid produced large amounts of solids in settled samples tentatively identified as calcium carbonate. Subsequent to acid flushing the pressure drop through the reactor returned to its original value.

Test Period 3 (November-December, 1980)

Before beginning these tests, mixers were installed in the sludge storage tank to provide a greater degree of uniformity in the sludge pumped to the reactor. In addition the boiler heating capacity was increased so that higher maximum reaction temperatures of 230^{0}C and a longer reaction zone could be attained.

This series of tests produced data on COD reductions, nitrogen and metals. Scaling problems were again experienced and the reactor was washed with nitric acid twice in December. The wash procedure consisted of pumping approximately 150 gallons of dilute (approximately 8%) nitric acid downhole at about 5 gpm followed by a water rinse after 20 minutes. This procedure was repeated as necessary to restore pressure drop through the system to normal level after which a one hour water rinse was performed. Reactor operation during this period was generally quite stable with the reactor operating unattended sixteen hours per day. Periodic minor mechanical problems occurred but operation was relatively trouble free.

Test Period 4 (March, 1981)

Upon completion of the December run the next step in the program was to obtain data on reactor performance at 260^{0}C. In order to reach this temperature, the reactor boiler and heat exchanger pump were replaced with larger equipment. In addition, to achieve the downhole pressure (680 psi) required by the increased temperature, air and sludge inlet pressure to the reactor were increased from 150 psi, to 400 psi, necessitating the installation of a larger compressor. These modifications in effect simulated the reaction conditions of a 260^{0}C reactor 3,000 feet long, conditions approximating those expected with a full size reactor. A COD reduction of 40-55% was anticipated at these operating conditions. The test run was halted after five days due to a leak in the reactor upcomer resulting in heat exchanger cooling water being lost to the reactor. Upon pulling the upcomer it was found that it had been partially crushed resulting in a crack caused, it is believed, by repeatedly opening the reactor discharge valve too quickly. Inspection showed scaling on the reactor downcomer where the reactor temperature had reach 150^{0}C.

The COD reductions in this test series fell within the expected range of 40-55%, and show less variation than previous tests probably because of better sampling control and more steady state operating conditions.

Dissolved oxygen in the effluent for this test run was held between 1.0 and 4.0 mg/liter by adjusting the volumetric flow of air into the reactor.

OPERATING PROBLEMS

As the following summary shows, this test program provided valuable information on the operability of the equipment and materials which went into the PPR.

Process Control

Problem	Solution
Heat exchanger (Hx) fluid flow difficult to control.	Add variable speed drive to pump.
Reactor output pressure difficult to control.	Use control valve with finer adjustment or automatic PCV.
Low flow cutoff switch in Hx line failed because of stop-leak and oil contamination.	Use welded pipe in lieu of screw couplings to eliminate leaks. Don't use oil when installing upcomer.
Air flow control not adequate. Air flow affected by storage tank pressure fluctuation.	Use automatic control. Use a more sensitive pressure transducer.
Plant shut down because of power outage.	Install backup motor-generator set.
Plant required much operator attention. Limited steady state operation was achieved.	Design for automatic controls and data recording; emphasize design quality; incorporate redundant critical equipment.
Heat exchanger fluid too hot to pump.	Increase heat rejection capacity.
Poor solids separation in flotation tank.	Design better settling system.
Pressure gage on reactor output control destroyed by opening control valve too quickly.	Use slower acting valve or automatic valve actuator.

Problem	Solution
Reactor inlet filters plugged because fine screen filters were used in closed lines.	Don't use in-line filters. Install an in-line grinder.
Boiler experienced soot buildup and flame blowout. Ignition coil burned out.	Use premium quality boiler, and redundant boilers.
Sump and dilutant pumps failed.	Exercise preventive maintenance and provide standby pumps.
Injection of descaling acid into flow stream was difficult because topside equipment was not acid resistant.	Use acid resistant components, and better design.

Reactor Design

Problem	Solution
Scaling at low operating temperatures.	Make provision for nitric acid flush, either continuous trickle or periodic flush.
Well casing pushed out of ground by thermal expansion.	Prestress well casing in tension.
Heat exchanger line plugged at well bottom from poor flow geometry, use of black iron pipe, use of water as Hx medium, and from sediment buildup.	Incorporate sump, use stainless steel, use other Hx fluid, install filter.
Leak between Hx jacket and reactor.	Redesign for higher strength.

Problem	Solution
Various problems with water as Hx fluid.	Use low vapor pressure Hx oil.
Thermocouple failed because of environmental stresses down-hole.	Install redundant thermocouples, in protective tubes or inside air line.

SECTION 3

LBR TEST PROGRAM

LBR DESCRIPTION

The LBR vessel was fabricated in 1973 from a schedule 40, 316L stainless steel pipe 3.3 feet long with an inside diameter of 2.0 inches. The 316 and 304 stainless steels were more resistant to pit corrosion than carbon steel and were less expensive than the high nickel or chromium content stainless steels. The 316L was chosen over the 304L because the former was more easily welded.

Through one end of an otherwise sealed vessel was a 1/4 inch stainless steel tube for monitoring pressure and to provide entry and exit for sample and air (see Figure 4). Electrical resistance rods and cooling tubes were externally attached to the vessel. To control heating and cooling rates the electrical resistance rods were powered by a motor driven variable voltage transformer. Room temperature tap water flowed through the cooling tubes and was shut off or metered by a needle valve to control cool down rates. Thermocouples to monitor temperature were welded on the vessel's outer surface at several locations. The reactor vessel and attached thermocouples, electrical resistance rods and cooling tubes were insulated. This arrangement was mounted to permit 180^0 rotation in a vertical plane at seven and one-half seconds per oscillation to provide internal mixing of sample and air.

LBR OPERATION

The objectives of the LBR operation were to simulate the temperature, pressure and reaction time that a waste would experience in a full scale VTR and to produce quantitative data for wastes treated under those conditions. The LBR was designed to process wastes over a wide range of COD concentrations and at variable temperatures, pressures and reaction times. Any LBR run represents a unique temperature versus time profile for a VTR of a given diameter, depth and flow rate which can be accurately simulated above 350^0F by controlled heating and cooling in the LBR. Figure 5 compares the profile for a VTR and LBR simulation of that profile. The reaction time above 350^0F

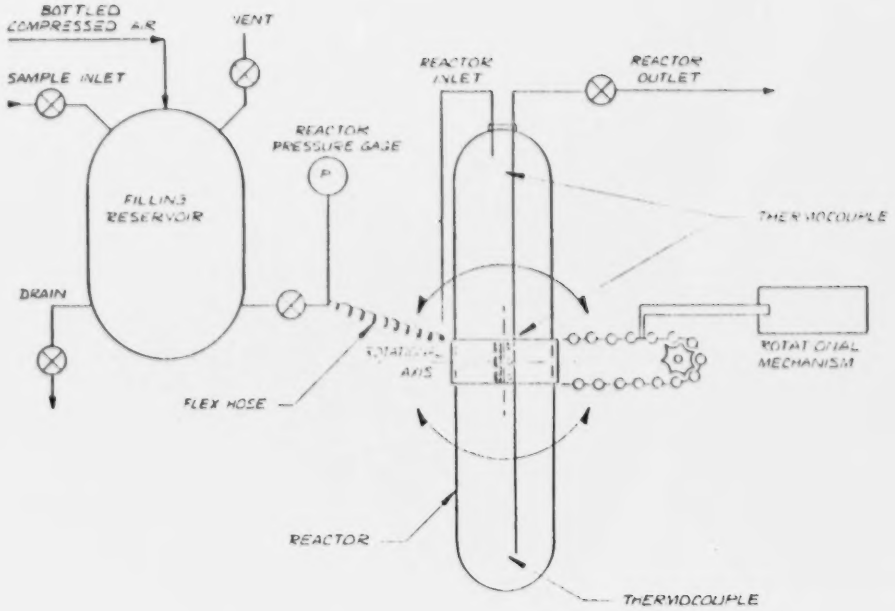

FIGURE 4. DRAWING OF THE LABORATORY BATCH REACTOR. (NOT PICTURED ARE THE HEATER RODS, COOLING LINES AND INSULATION)

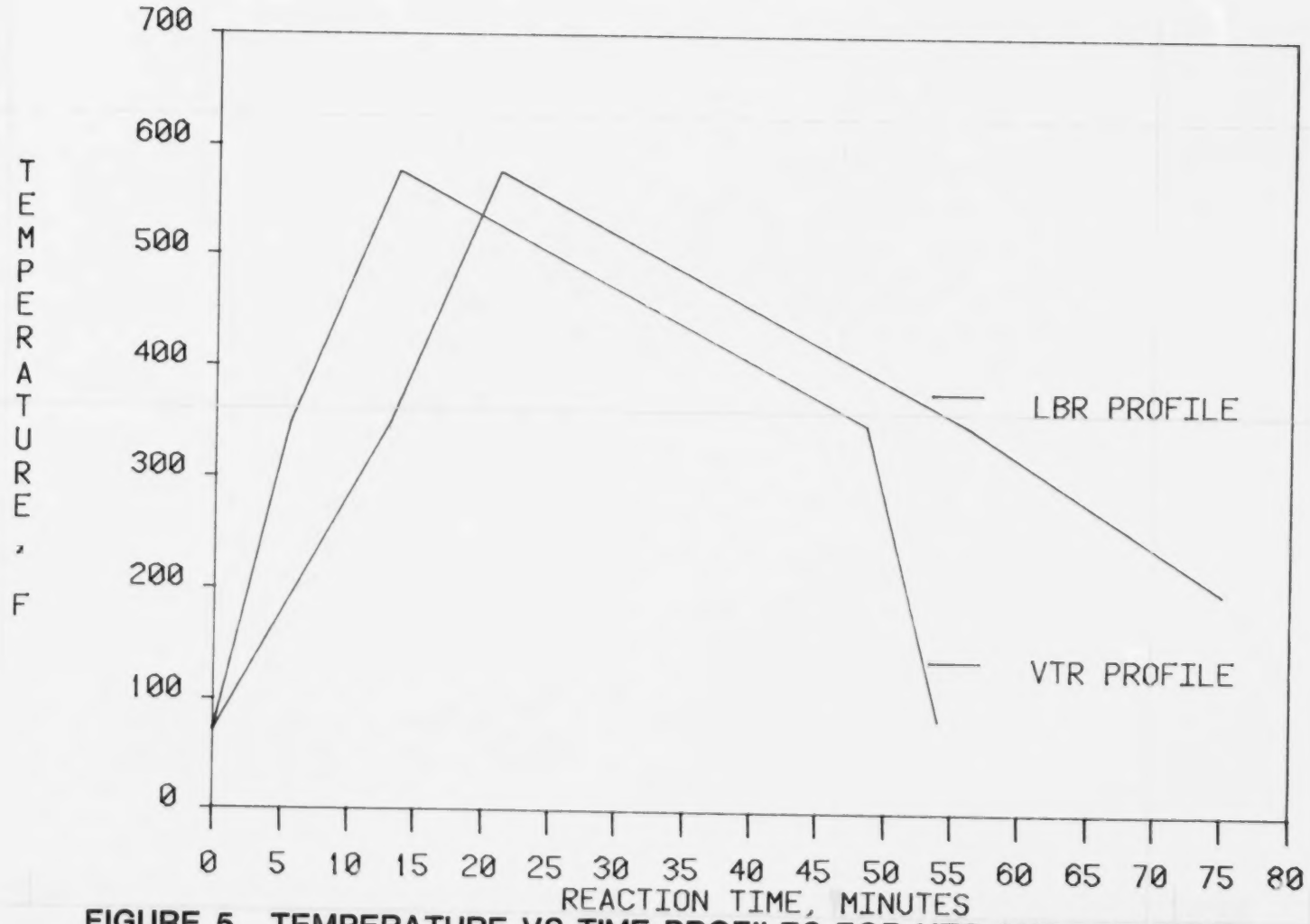

FIGURE 5. TEMPERATURE VS TIME PROFILES FOR VTR AND LBR RUNS

for each profile is the same, however the total residence time is different. The insulation required to retain the heat to meet the desired maximum temperatures limits the LBR's ability to heat up and cool down rapidly below approximately 350 F.

Compressed air was used to initially pressurize the system and provide enough oxygen to satisfy the stoichiometric requirements of the sample COD. Complete mixing of the air with the waste was accomplished by continuously oscillating the reactor. This action simulates the fluid dynamics of the VTR in which air, injected into the downcomer, rises with respect to the sludge but is ultimately carried down with the sludge stream.

In the LBR the increase in pressure is a function of the expansion of the air and waste as they are heated, where in the VTR the weight of the hydrostatic head above the waste is responsible for the downhole pressure. As with the VTR, the pressure in the LBR must always be great enough to keep the waste in the liquid phase. In aqueous solutions the high solubility and diffusibility of oxygen at elevated temperatures enables a strong driving force for wet air oxidation (9).

For a typical LBR run, a portion of sample, always less than half the total LBR volume, is placed inside the reactor. In the case of this project a sample size of 1300 mℓ was always used. Thus a discrete portion of sample is treated in the LBR where the VTR treats a continuous stream.

LBR SCALE RESEARCH

The objectives for LBR testing were to establish the oxidation characteristics of sludges from different sources and stages of treatment; to simulate as closely as possible the pilot scale VTR conditions with the LBR in order to obtain treatability data which predicts COD removal rates expected in a full scale VTR and to determine solids reductions, the fate of metals, nitrogen and phosphorus results and selected volatile organic compounds in VTR treated wastewaters.

Oxidation Characteristics of Sludges

The total chemical oxygen demand (TCOD), COD reduction, effluent soluble COD (SCOD) and effluent total biological oxygen demand (TBOD) of each sludge were evaluated to characterize the oxidation rates of sludges at different stages of treatment.

Table 1 lists the sources of each sludge and the type of sludge. For further source and sample identification, Appendix B contains a description of each wastewater treatment

plant and describes from where in the plant the sludge sample was taken.

Each diluted (with tap water) sludge sample was treated for reaction times of thirty and sixty minutes above 350^0F and to the maximum reaction temperatures of 400, 500, 600 and 650^0F. The LBR was initially pressurized for all samples with 180 psi of compressed air.

TABLE 1. THE SOURCE OF EACH SLUDGE AND ITS STAGE OF TREATMENT

SOURCE OF SLUDGE	STAGE OF TREATMENT
Denver Northside W.W.T.P. Denver, Colorado	digested sludge
Denver Northside W.W.T.P. & Denver Metro W.W.T.P. Denver, Colorado	blended sludge
Longmont W.W.T.P. Longmont, Colorado	primary sludge
Brush W.W.T.P. Brush, Colorado	primary sludge with food processing waste
Aurora W.W.T.P. Aurora, Colorado	domestic waste

Table 2 summarizes the COD reduction data in Tables C-1, C-2, C-3, C-4 and C-5 for LBR runs on each sludge type and compares the reductions obtained for sludges at five stages of treatment. Figures 6 and 7 show COD reduction versus maximum reaction temperature for thirty and sixty minute reaction times respectively.

As the reaction temperature increases the COD reduction increases for each sludge except for primary sludge with food processing waste in Figure 6. The low COD reduction at 500^0F is due probably to sample handling or COD analysis rather than a difference in the sludge type because at 400, 600 and 650^0F the COD reduction for primary sludge with food processing waste falls in line with reductions obtained by the other sludge types in Figure 6.

Increased reaction time from thirty to sixty minutes results in greater COD removals for each sludge except domestic waste as

TABLE 2. COMPARISON OF TOTAL COD REDUCTION DATA FOR SLUDGES AT FIVE STAGES OF TREATMENT*

TYPE OF SLUDGE	THIRTY MINUTE REACTION TIMES				SIXTY MINUTE REACTION TIMES			
	400°F	500°F	600°F	650°F	400°F	500°F	600°F	650°F
DIGESTED	13%	54%	76%	82%	35%	63%	79%	83%
BLENDED	27%	52%	75%	80%	37%	65%	78%	81%
PRIMARY	9%	50%	63%	74%	-	53%	69%	78%
PRIMARY W/FOOD PROCESSING WASTE	21%	20%	75%	86%	15%	-	61%	80%
DOMESTIC WASTE	30%	44%	50%	74%	16%	55%	70%	77%
AVERAGE & STANDARD DEVIATION	20 ± 9%	44 ± 14%	68 ± 11%	79 ± 5%	26 ± 12%	59 ± 6%	71 ± 7%	80 ± 2%

* COD DATA IS LISTED IN TABLES 1,2,3,4, AND 5 OF APPENDIX C.

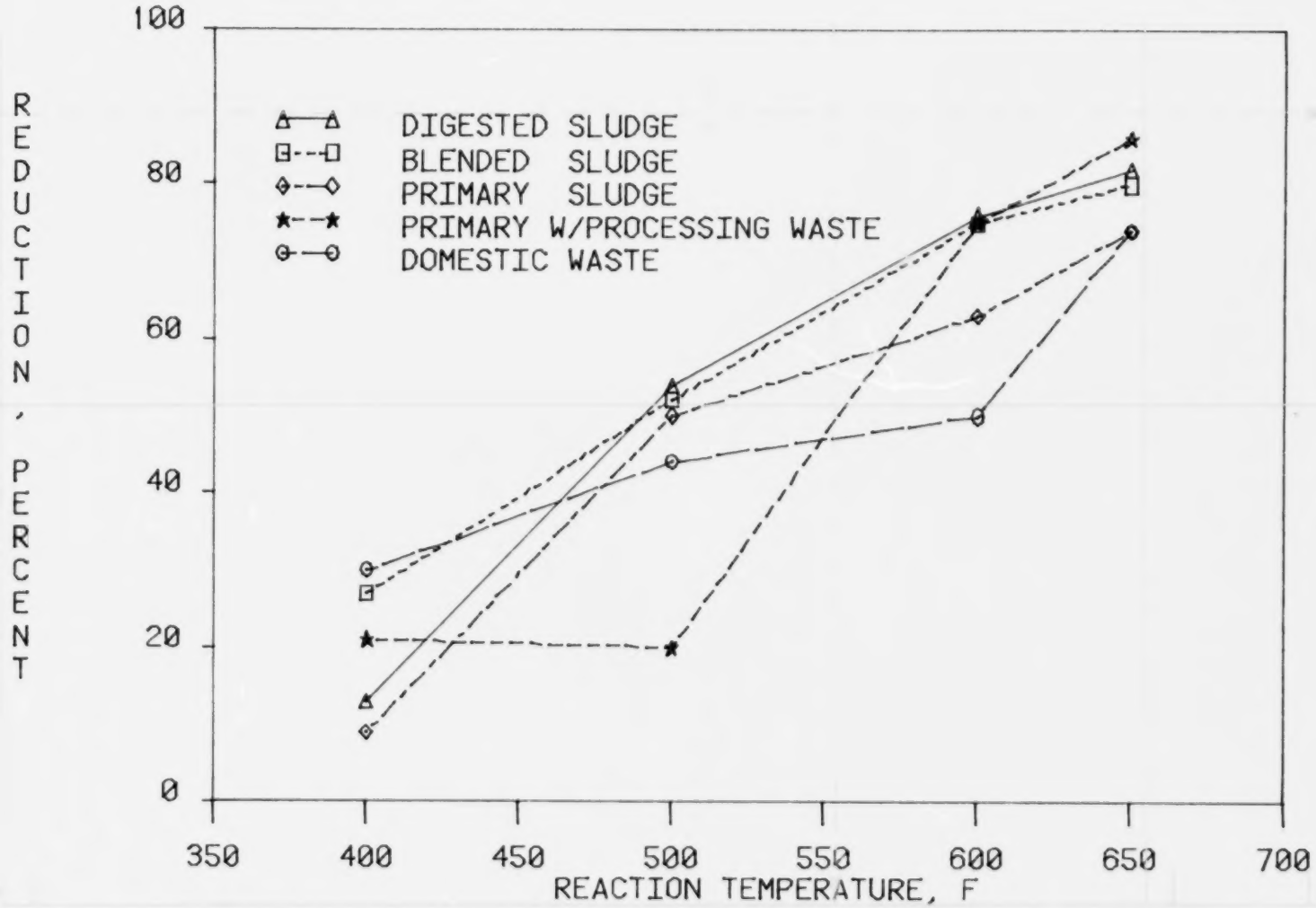

FIGURE 6. LBR TCOD RDXN DATA FOR 30 MIN. REACTION TIMES FOR SLUDGES AT 5 STAGES OF TREATMENT

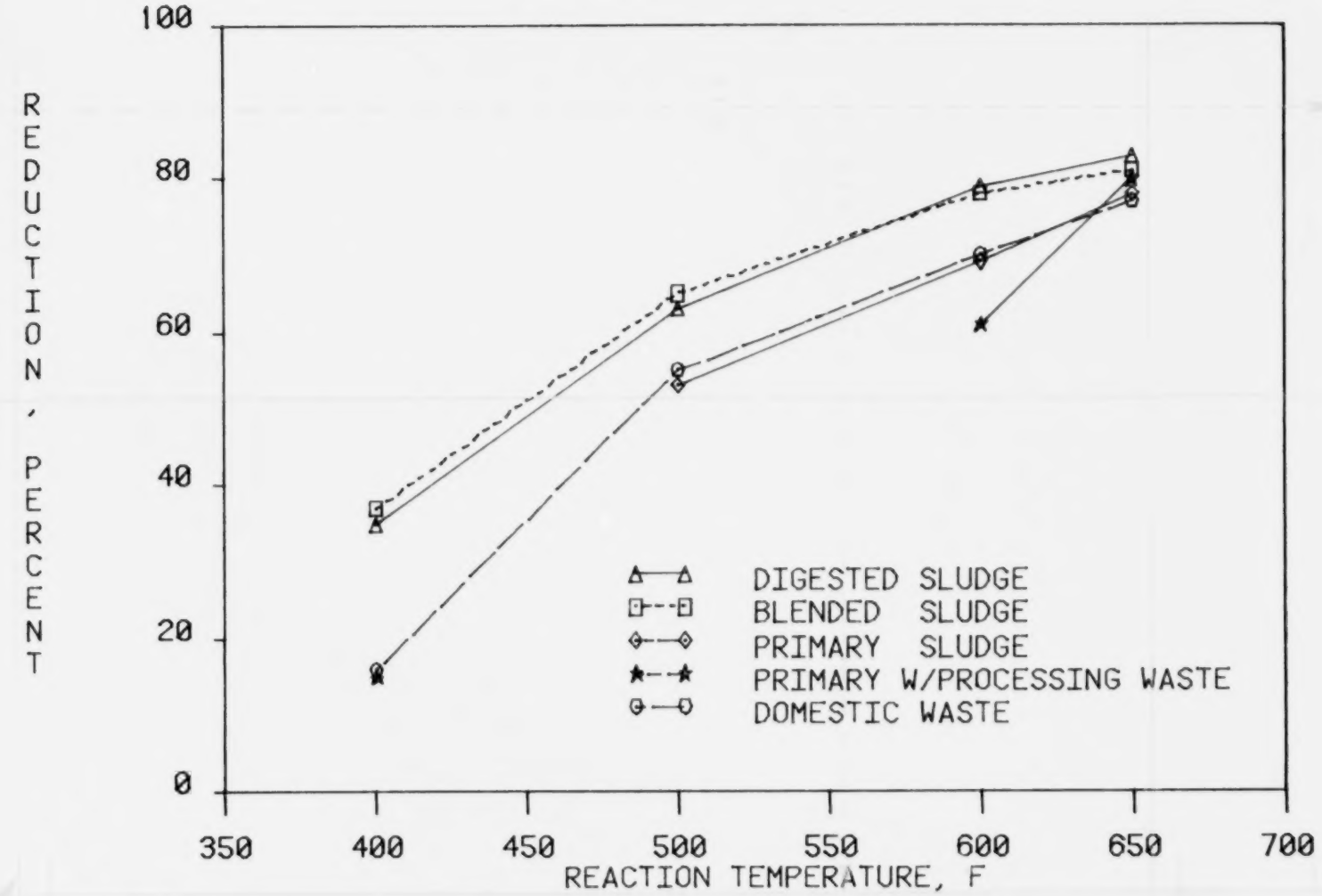

FIGURE 7. LBR TCOD RDXN DATA FOR 60 MIN. REACTION TIMES FOR SLUDGES AT 5 STAGES OF TREATMENT

Figures 8, 9, 10, 11 and 12 show. The COD reduction at 400^{0}F, in Figure 12, is higher for the LBR run at thirty minutes than at sixty minutes. This is also probably due to sample handling or analysis problems because at 500, 600 and 650^{0}F the COD reduction is greater in the runs at sixty minutes.

Typically, larger differences in COD removals occur between sixty and thirty minute LBR runs at 400^{0}F than at 500 or 600^{0}F as Figure 8 shows. At 650^{0}F the COD removal between sixty and thirty minute reaction times is virtually the same (see Figures 8, 9, 10, 11 and 12). This effect is due to the production of low to medium molecular weight compounds which require elevated temperatures rather than increased reaction times to undergo further oxidation.

The percent of total effluent COD which is soluble (%SCOD/TCOD) for LBR runs on each sludge is listed in Table 3. A high SCOD/TCOD percentage indicates that the particulate ash contributes a correspondingly low amount to the TCOD. In the case of a 100% SCOD/TCOD in the effluent an inert particulate ash would be expected. There are many cases in Table 3 where the %SCOD/TCOD approaches or exceeds 100%. At temperatures above 350^{0}F the large molecular weight compounds undergo hydrolysis and oxidation to form lower molecular weight compounds which become soluble resulting in a high effluent %SCOD/TCOD. These soluble compounds are available for biological degradation (10,11).

As the reaction temperature and time increases the portion of effluent BOD (%TBOD/TCOD) remaining also increases indicating increased effluent biodegradability. Table 4 lists the %TBOD/TCOD in the effluent of LBR runs on each sludge.

A pH drop between influent and effluent samples indicates the presence of low molecular weight acidic compounds and evolved carbon dioxide (CO_2)(12) resulting from the oxidation reaction. As Table 5 shows, LBR runs at elevated temperatures or increased reaction times do not result in a lower effluent pH.

Sludges from various sources may contain other components which resist oxidation, result in low percent COD reductions. The sludges from Denver Northside, Denver Metro, Longmont and Brush treatment facilities contain varying amounts of industrial wastes, uncharacterized in this report, which might effect the oxidation rates.

"The main objectives of conventional wastewater treatment processes are the reduction of BOD, suspended solids and pathogenic organisms." (13) At the different stages of treatment each sludge will contain varying amounts of low and high molecular weight organic compounds, the former being refractory and

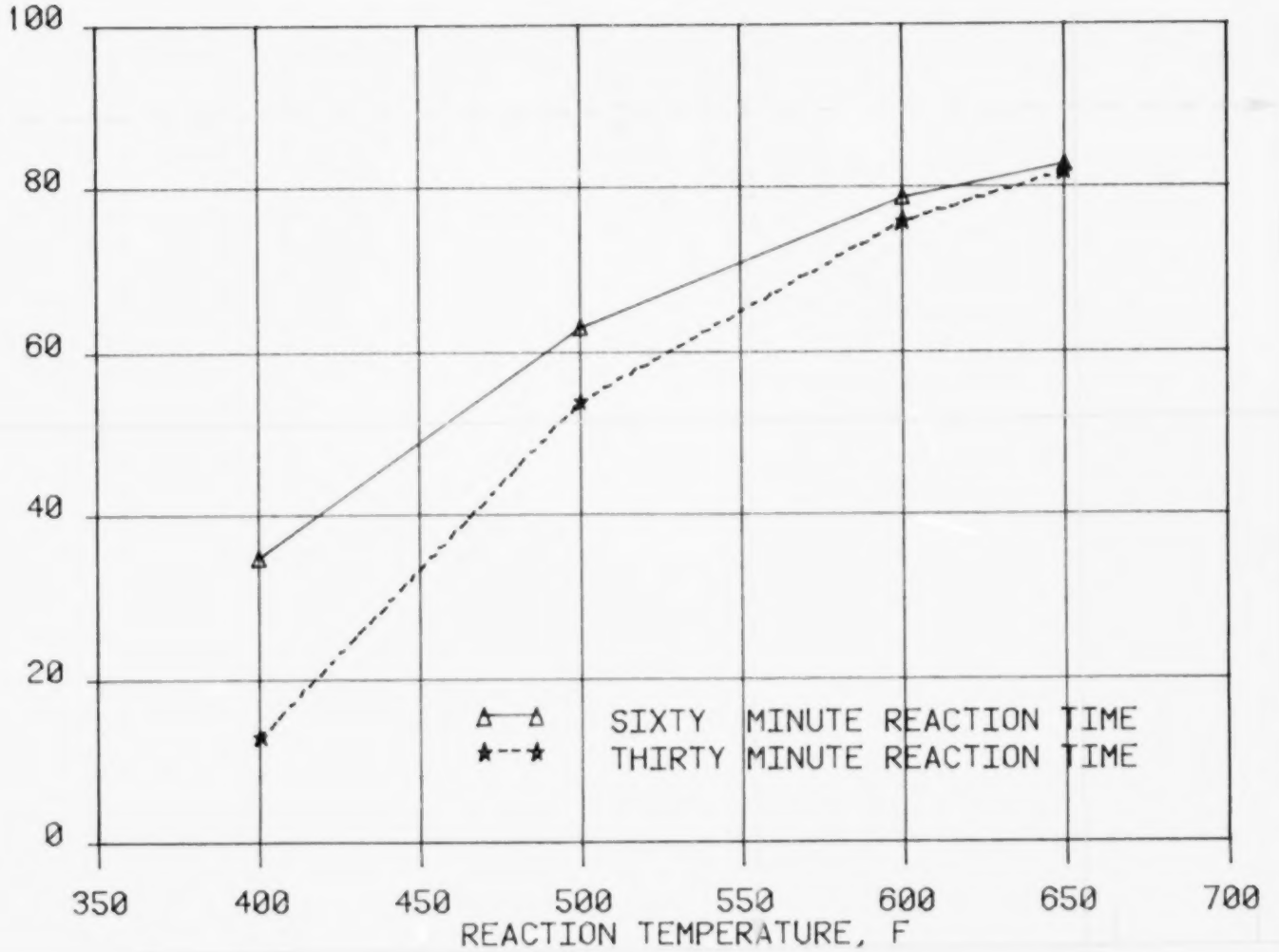

FIGURE 8. LBR COD RDXN DATA FOR DIGESTED SLUDGE AT 30 & 60 MINUTE REACTION TIMES

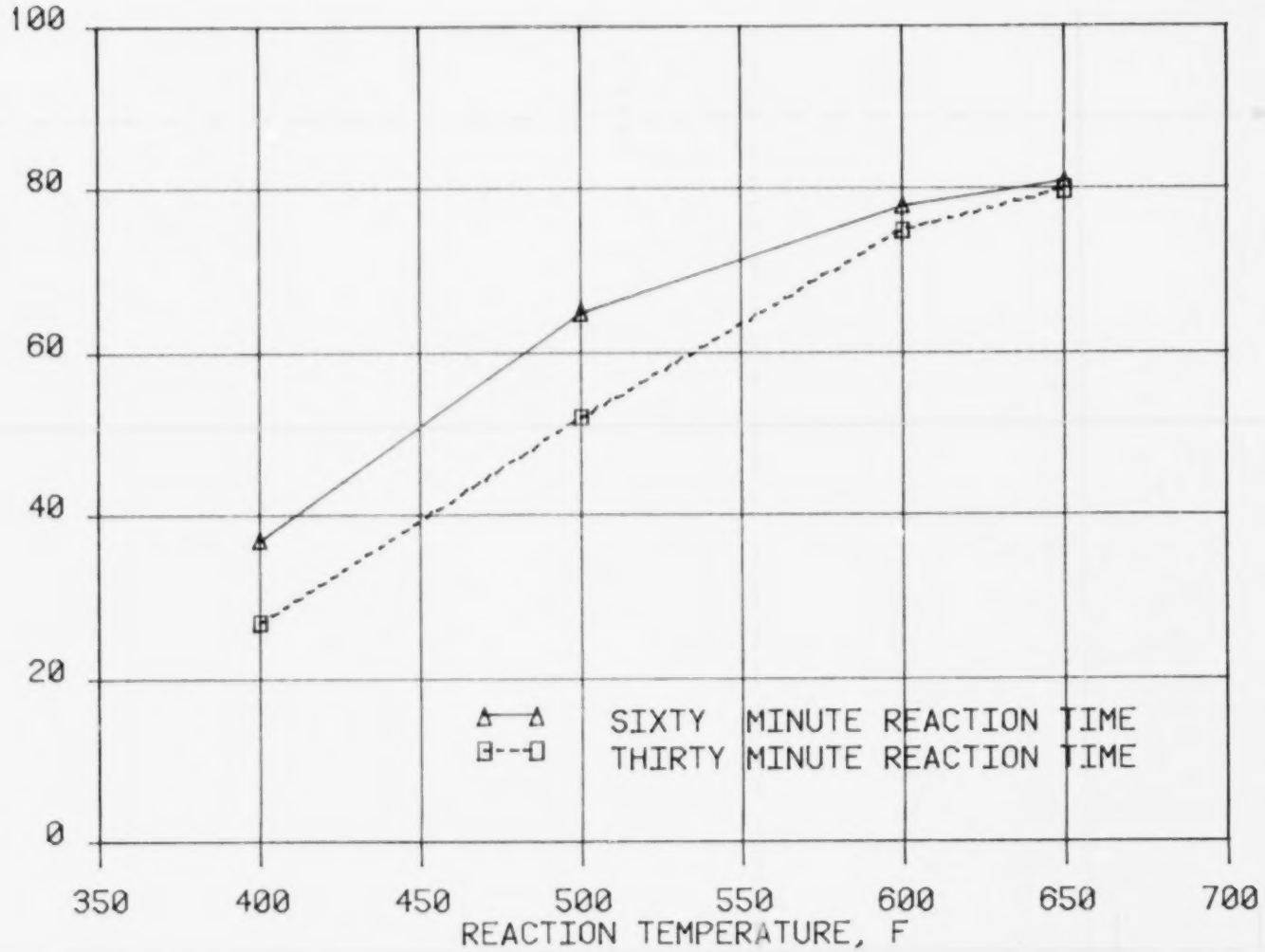

FIGURE 9. LBR COD RDXN DATA FOR BLENDED SLUDGE AT 30 & 60 MINUTE REACTION TIMES

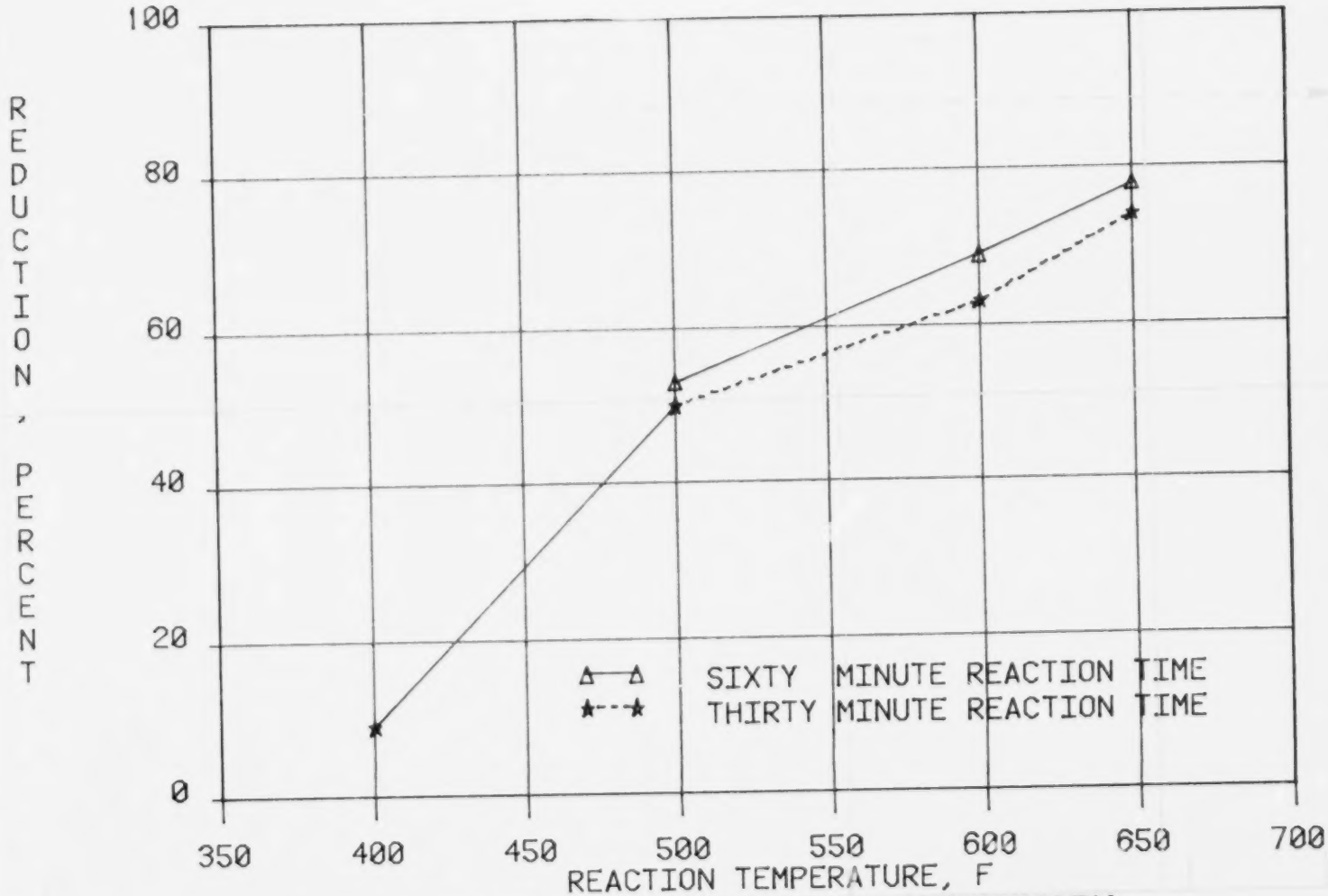

FIGURE 10. LBR COD RDXN DATA FOR PRIMARY SLUDGE AT 30 & 60 MIN. REACTION TIMES

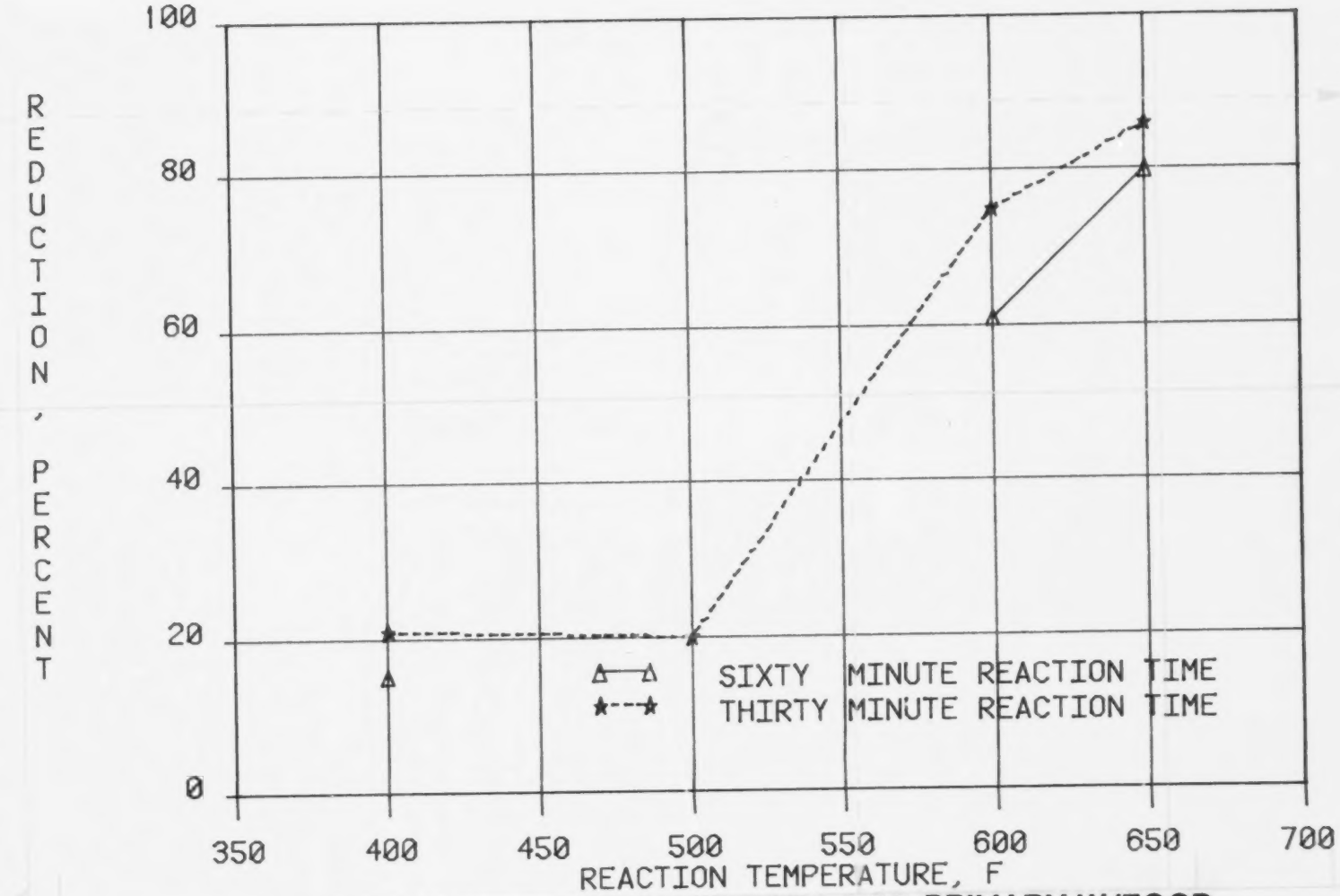

FIGURE 11. LBR COD RDXN DATA FOR PRIMARY W/FOOD PROCESSING WASTE AT 30 & 60 MIN. RXN TIMES

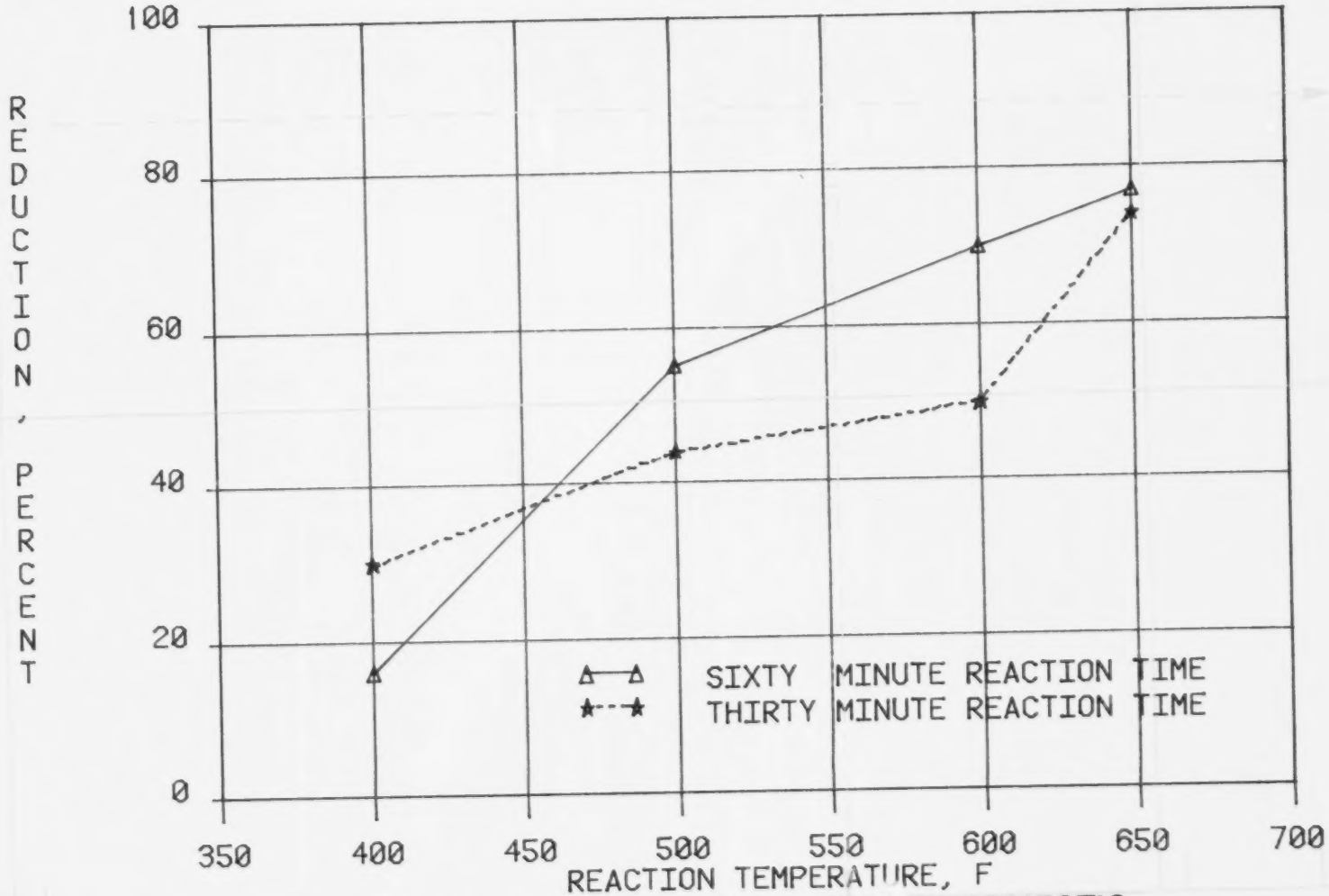

FIGURE 12. LBR COD RDXN DATA FOR DOMESTIC WASTE AT 30 & 60 MIN. REACTION TIMES

TABLE 3. COMPARISON OF PERCENT SCOD/TCOD IN THE EFFLUENT OF RUNS ON SLUDGES AT FIVE STAGES OF TREATMENT*

SLUDGE TYPE	THIRTY MINUTE REACTION TIME				SIXTY MINUTE REACTION TIME			
	400°F	500°F	600°F	650°F	400°F	500°F	600°F	650°F
DIGESTED	68	90	99	95	84	89	94	102
BLENDED	76	85	106	100	82	90	105	106
PRIMARY	57	93	65	69	-	-	91	56
PRIMARY W/FOOD PROCESSING WASTE	68	83	-	71	68	-	100	45
DOMESTIC WASTE	98	74	50	98	67	-	54	-

* SCOD AND TCOD DATA FOR EACH SLUDGE TYPE ARE CONTAINED IN TABLES 1,2,3,4, and 5 OF APPENDIX C.

TABLE 4. COMPARISON OF PERCENT TBOD/TCOD IN THE EFFLUENT OF RUNS ON SLUDGES AT FIVE STAGES OF TREATMENT*

SLUDGE TYPE	THIRTY MINUTE REACTION TIME				SIXTY MINUTE REACTION TIME			
	400°F	500°F	600°F	650°F	400°F	500°F	600°F	650°F
DIGESTED	44	57	67	72	50	66	69	73
BLENDED	53	65	69	68	60	73	71	71
PRIMARY	22	-	70	70	-	56	76	80
PRIMARY W/FOOD PROCESSING WASTE	43	72	93	74	80	-	91	125
DOMESTIC WASTE	61	41	45	75	-	60	68	76

* TBOD AND TCOD DATA FOR EACH SLUDGE TYPE ARE CONTAINED IN TABLES 1,2,3,4 AND 5 IN APPENDIX C.

TABLE 5. INFLUENT AND EFFLUENT pH DATA FOR RUNS ON SLUDGES AT FIVE STAGES OF TREATMENT*

	THIRTY MINUTE REACTION TIME							
	400°F		500°F		600°F		650°F	
SLUDGE TYPE	IN	OUT	IN	OUT	IN	OUT	IN	OUT
DIGESTED	7.8	7.1	7.6	6.7	7.6	7.5	7.6	7.0
BLENDED	7.4	5.7	6.9	5.0	6.9	6.6	7.0	7.0
PRIMARY	5.7	3.9	5.5	4.1	5.6	4.8	5.6	4.8
PRIMARY WITH FOOD PROCESSING WASTE	5.2	4.0	5.8	4.8	6.0	4.8	5.7	5.1
DOMESTIC WASTE	6.0	5.6	5.5	6.2	6.0	5.5	6.0	6.4

	SIXTY MINUTE REACTION TIMES							
	400°F		500°F		600°F		650°F	
SLUDGE TYPE	IN	OUT	IN	OUT	IN	OUT	IN	OUT
DIGESTED	7.8	6.8	7.6	6.5	7.6	7.0	7.6	7.6
BLENDED	7.4	5.7	7.0	6.7	7.1	6.8	6.6	6.0
PRIMARY	5.6	NR	5.7	NR	5.5	4.8	5.6	5.0
PRIMARY W/FOOD PROCESSING WASTE	5.5	4.1	5.6	4.4	6.0	5.0	5.3	5.0
DOMESTIC WASTE	5.9	4.6	5.6	5.4	5.7	6.6	5.6	6.8

NR - NOT RUN

* pH DATA FOR EACH SLUDGE TYPE ARE CONTAINED IN TABLES 1,2,3,4, and 5 OF APPENDIX C.

requiring higher reaction times and temperatures to achieve significant COD and BOD reductions. Figures 6 and 7 show that despite sludge differences, LBR runs on each sludge type obtained a near 80% COD reduction at 650^{0}F.

Correlation between LBR and PPR COD Reduction Data

The objective was to simulate the temperature and time conditions of the PPR with the LBR to obtain COD reductions which were compared to the PPR COD reductions. The parameters of sludge and air flow rates, sludge concentration and temperatures at various depths from a PPR run were entered into a computer modeling program which generated a temperature versus time profile used for an LBR run.

The COD reductions obtained from LBR runs corresponding to reaction times and temperatures similar to those conditions in the PPR are compared with PPR COD reductions in Table 6. Data from PPR runs in October 1979 are low compared to the data for 15 and 20 minute LBR runs performed at 445^{0}F. The remaining COD reductions obtained for PPR runs fall within the standard deviation range of COD reductions established by multiple LBR runs at the temperatures and times listed in Table 6 supporting the use of LBR generated treatability studies to model expected COD reduction rates.

While COD reductions approached 50% in the PPR, as much as 80% COD reduction is expected for a full scale VTR where higher temperatures and pressures can be attained. Figure 13 shows the approximately thirty minute PPR run data for 440 and 510^{0}F. from Table 6 and thirty minute LBR data from Table C-6 for reaction temperatures ranging from 400 to 650^{0}F. A full scale VTR would have a reaction time longer than thirty minutes because of its length but as Figures 8, 9, 10, 11 and 12 show there is little difference in COD reduction between thirty and sixty minute reaction times at elevated temperatures.

Reductions and Data from Chemical Analysis

LBR and PPR solids reduction data appears in Tables 7 and 8. The total volatile solids (TVS) and total volatile suspended solids (TVSS) reductions for the PPR in Table 8 are suspiciously low compared to corresponding total solids (TS) and total suspended solids (TSS) reductions. The PPR data from runs at known conditions in Table 8 fall within the standard deviation ranges of LBR data for thirty minute runs at 500^{0}F in Table 7.

Figures 14 and 15 graphically summarize average solids reductions from sludges treated in the LBR (see Table 7). These data indicate that increased reaction times are less important than increased reaction temperatures for solids removal.

TABLE 6. CORRELATION DATA BETWEEN PILOT AND LABORATORY BENCH SCALE REACTORS

SAMPLING PERIOD	PILOT SCALE VTR DATA*			LBR DATA**		
	REACTION TEMPERATURE °F	REACTION TIME MINUTES	COD REDUCTION %	REACTION TEMPERATURE °F	REACTION TIME MINUTES	COD REDUCTION %
OCTOBER 1979	435	17.5	11.9 ± 6.8%	445	15	21.4 ± 2.0%
				445	20	24.6 ± 6.3%
JULY 23, 1980	440	27	38.1%	445	30	35.9 ± 14.0%
JULY 24-25, 1980	440	30	29.7 ± 5.5%	445	30	35.9 ± 14.0%
NOVEMBER 1980	420	10.6	24.9 ± 8.9%	445	15	21.4 ± 2.0%
DECEMBER 1980	433	14	22.0 ± 9.4%	445	15	21.4 ± 2.0%
MARCH 1981	510	28	42.6 ± 9.4%	500	30	47.2 ± 10.1%

* TABLE 1 OF APPENDIX D
** TABLE 6 of APPENDIX C

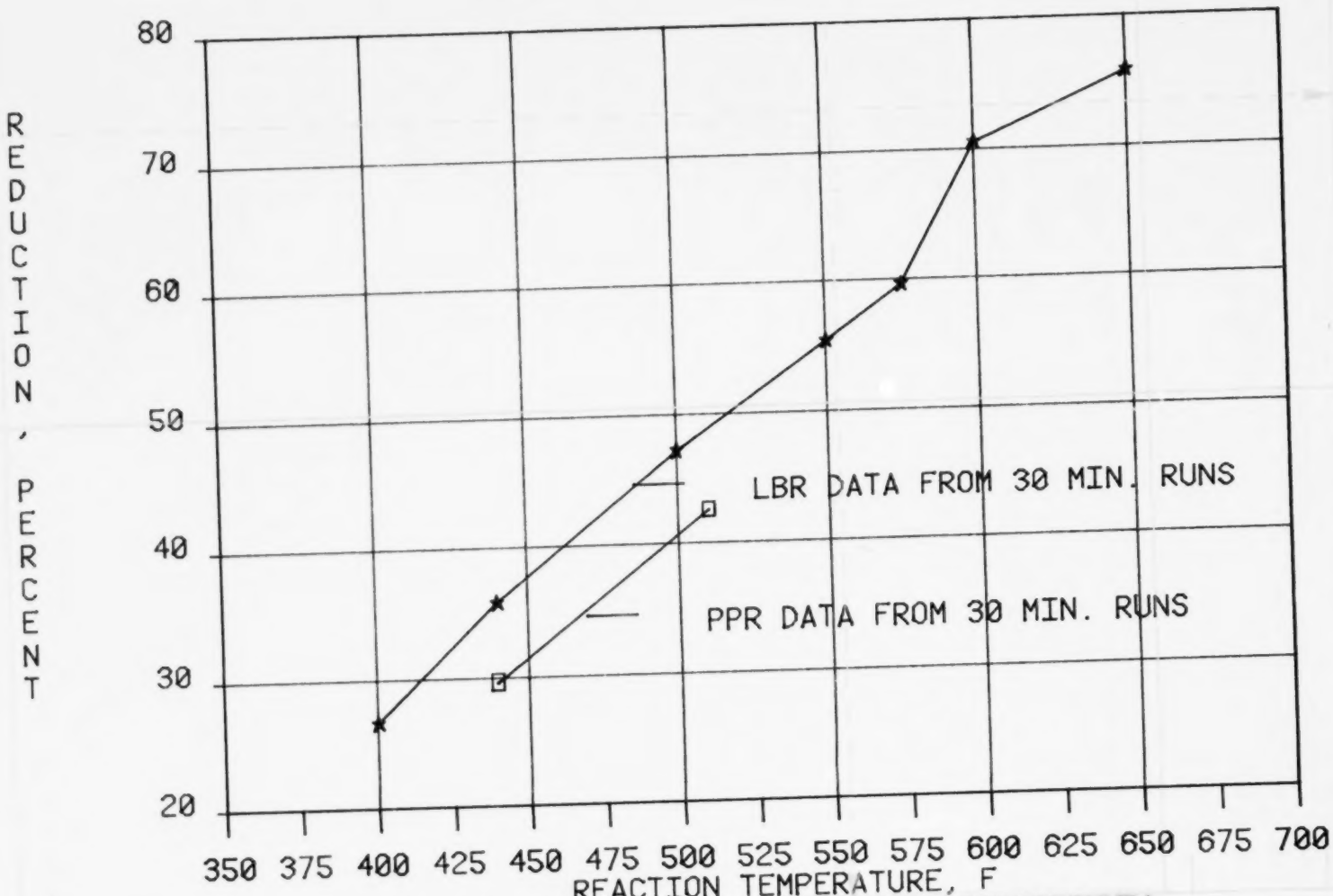

FIGURE 13. LBR AND PPR COD REDUCTION DATA

TABLE 2. SUMMARY OF LBR SOLIDS REDUCTION DATA*

	THIRTY MINUTES				SIXTY MINUTES			
	400°F	500°F	600°F	650°F	400°F	500°F	600°F	650°F
% TS REDUCTION	42 ± 27%	42 ± 19%	64 ± 14%	72 ± 7%	38 ± 18%	64 ± 7%	64 ± 6%	68 ± 7%
% TVS REDUCTION	52 ± 21%	59 ± 17%	89 ± 4%	94 ± 4%	50 ± 14%	17 ± 19%	89 ± 5%	88 ± 4%
% TSS REDUCTION	63 ± 15%	74 ± 9%	86 ± 9%	80 ± 18%	46 ± 16%	81 ± 16%	89 ± 11%	80 ± 14%

TABLE 3. SUMMARY OF PPR SOLIDS REDUCTION DATA**

PPR CONDITIONS:	500 F/28 MIN.	510-515 F/28 MIN.	UNKNOWN	440/30 MIN.
% TS REDUCTION	54	64	41	-
% TVS REDUCTION	42	-	26	-
% TSS REDUCTION	70	75	74	71 ± 18%
% TVSS REDUCTION	43	-	69	-

* SUMMARY OF LBR SOLIDS DATA FROM TABLES 13, 14, 15, 16, AND 17 OF APPENDIX C.

** SUMMARY OF PPR SOLIDS DATA FROM TABLES 10, 11, AND 12 OF APPENDIX D.

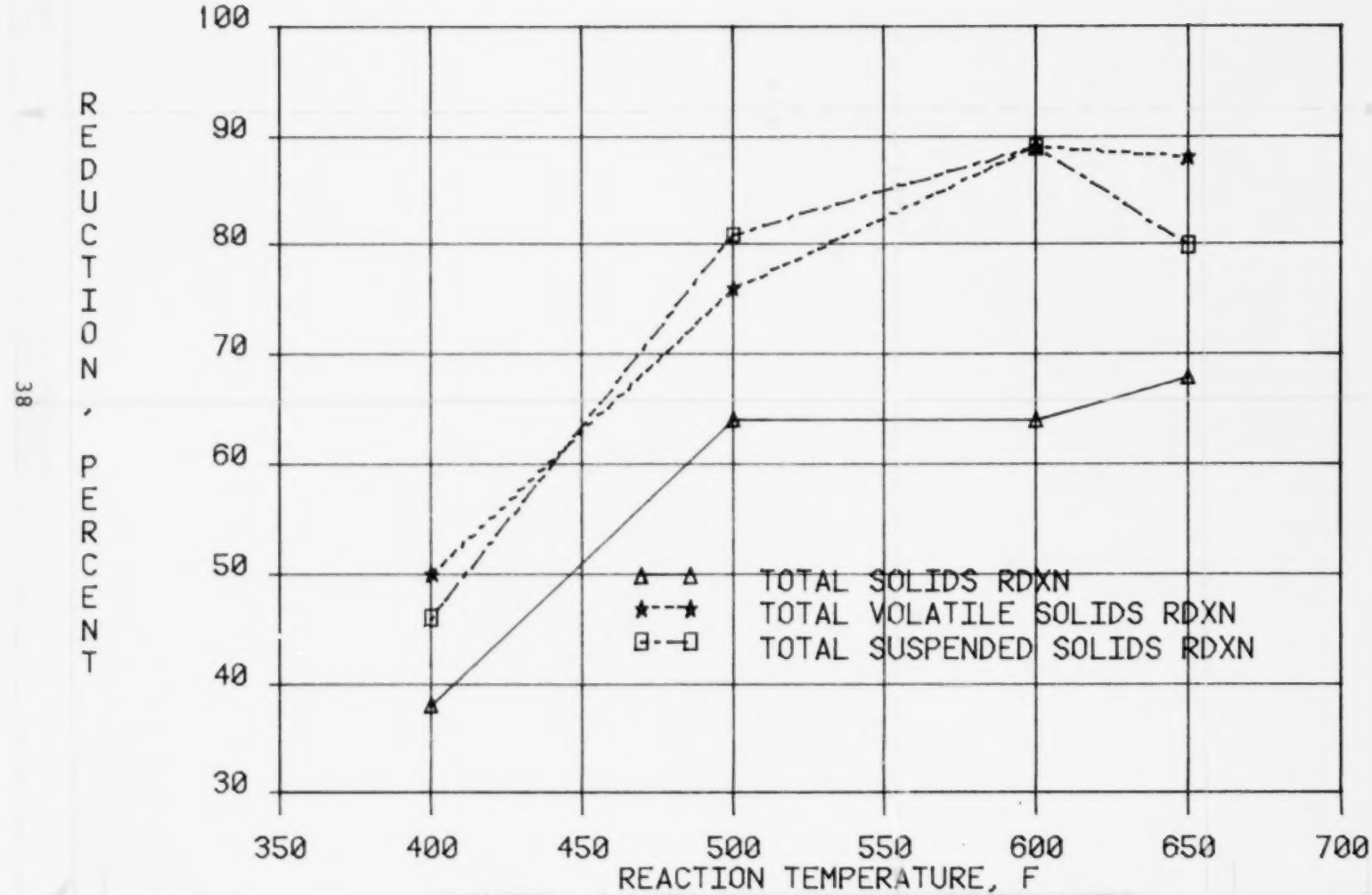

FIGURE 14. LBR SOLIDS REDUCTION DATA SIXTY MINUTE REACTION TIMES

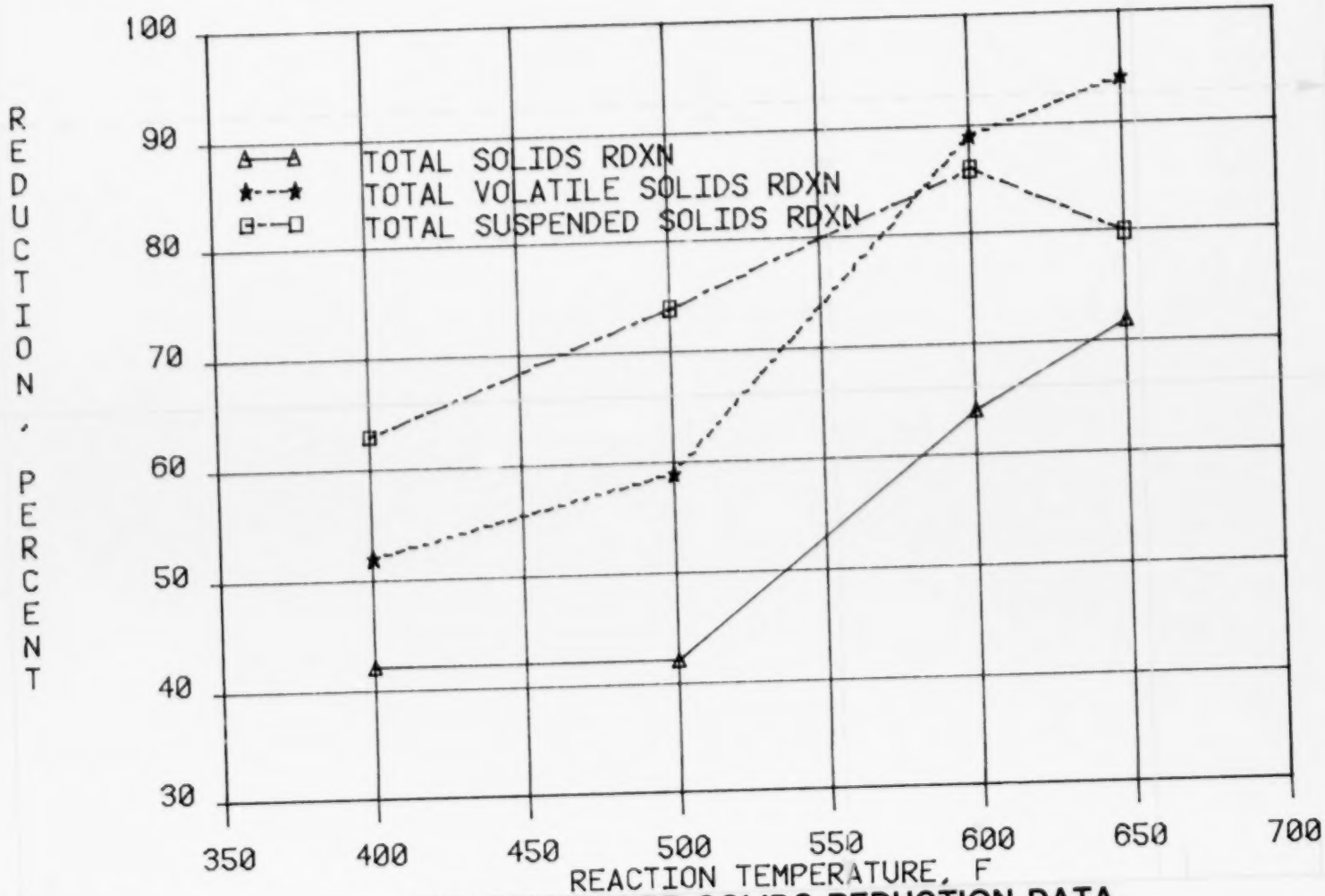

FIGURE 15. LBR SOLIDS REDUCTION DATA THIRTY MINUTE REACTION TIMES

At 650°F the TS and TSS removals approach 80% for thirty and sixty minute LBR runs while TVS removal approaches 95% resulting in a straw colored effluent that contains less than 25% of the original influent solids volume. Solids reductions are related to increased %SCOD/TCOD because as solid organics are hydrolyzed into smaller units they are solublized adding to the SCOD. The remaining effluent ash (2.5% in the PPR, see Table D-11) is easily dewatered.

LBR and PPR metal concentration data in Tables C-18, C-19, C-20, D-13 and D-14 show that at times a significant increase or decrease in concentration between influent and effluent samples occurred. This effect may indicate the precipitation of metals on the inside wall of the reactor vessel and their being flushed out at unpredictable times. Also, the poorly understood interacting effects of metal complexing, solubility, adsorption and desorption at high temperatures prevent a definitive explanation of this phenomena.

Selected metals analyses have been made on LBR and PPR effluents to determine whether the metals remain in the soluble or particulate fractions. The data in Tables 9 and 10 show that the metal concentration in the soluble effluent of both PPR and LBR runs is much lower than the total effluent metal concentration indicating that the particulate ash contains much of the remaining effluent metals.

PPR and LBR nitrogen data in Tables D-15, D-16 indicate that total kjeldahl nitrogen (TKN) does not change appreciably between influent and effluent samples. This would be expected as TKN is defined as the sum of free-ammonia and of organic nitrogen compounds. Organic nitrogen is probably converted into ammonia which would explai.. the increase in ammonia nitrogen (mg NH_3-N/ℓ) between influent and effluent samples. Nitrate nitrogen (mg NO_3^--N/ℓ) decreases slightly according to PPR data.

Although no analysis for phosphorus was made on LBR samples PPR sample analysis, shown in Table D-15, indicate a decrease of 18 mg/ℓ or more for total phosphorus and orthophosphorus except for one date. Orthophosphorus increased slightly on March 21, 1981. Analysis of the scale which occurred in the PPR confirmed the presence of phosphates (probably as $Ca_3(PO_4)_2$) (14). The biological step in a wastewater treatment plant converts polyphosphates to orthosphates so that phosphorus in the plant effluent is about 80% orthophosphate (15). Orthophosphate reacts with calcium and hydroxide at neutral to alkaline pH values to form an insoluble hydroxyaptite and chemical precipitation of phosphorus occurs with iron or aluminum at acid pH values (16).

Off gas analysis from a PPR run on December 23, 1980,

TABLE 9. PRR METAL CONCENTRATION DATA

METAL, mg/ℓ	12-10-80*		12-15-80*		12-21-80*		3-19-81**		3-20-81**		3-21-81**	
	TE***	SE***	TE	SE	TE	SE	TE	SE	TE	SE	TE	SE
CADMIUM	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	NR	NR	NR	NR	NR	NR
CALCIUM	NR	NR	NR	NR	NR	NR	33	25	27	13	42	19
CHROMIUM TOTAL	0.26	0.03	0.32	0.03	0.27	0.03	0.28	0.14	0.20	0.08	0.30	0.09
CHROMIUM^{+6}	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	NR	NR	NR	0.01	NR
COPPER	0.60	0.22	0.56	0.23	0.56	0.25	0.90	0.65	0.68	0.35	1.6	0.84
IRON	5.6	<0.02	6.5	<0.02	6.1	<0.02	0.81	3.8	0.52	1.8	1.1	3.0
LEAD	0.061	0.005	0.086	0.007	0.062	0.005	0.190	0.128	0.134	0.037	0.240	0.092
MAGNESIUM	NR	NR	NR	NR	NR	NR	20	15	15	8.6	22	10
NICKEL	0.05	0.05	0.05	<0.05	0.06	<0.05	<0.05	<0.05	<0.05	<0.05	0.09	0.06
ZINC	NR	NR	NR	NR	NR	NR	2.08	1.40	1.38	0.51	2.07	0.83

* PPR CONDITIONS: 433 F/14 MINUTES (SEE TABLE 13 OF APPENDIX D).

** PPR CONDITIONS: AVERAGE 510 F/28 MINUTES (SEE TABLE 14 OF APPENDIX D).

*** TE = TOTAL EFFLUENT, SE = SOLUBLE EFFLUENT

TABLE 10. LBR METAL CONCENTRATION DATA

METAL, mg/ℓ	650°F-30 MIN.*		650°F-60 MIN.*		650°F-60 MIN.**		650°F-60 MIN.**	
	EFF.	SOL. EFF.	EFF.	SOL. EFF.	EFF.	SOL. EFF.	EFF.	SOL. EFF.
CADMIUM	0.05	<0.01	0.02	0.06	<0.01	<0.01	<0.01	<0.01
CHROMIUM, TOTAL	7.0	3.7	1.8	1.2	0.13	0.05	0.06	0.03
CHROMIUM^{+6}	2.46	1.49	0.22	0.08	NR	NR	NR	NR
COPPER	2.5	0.05	0.70	0.07	1.3	0.08	0.48	0.14
IRON	32	0.19	10	0.21	8.8	<0.02	0.12	NR
LEAD	4.2	0.016	0.83	0.052	0.203	<0.005	0.058	0.007
NICKEL	0.51	0.12	0.12	<0.05	0.07	<0.05	<0.05	<0.05
ZINC	4.0	0.04	1.25	0.16	NR	NR	NR	NR

NR - NOT RUN

* SUMMARY FROM TABLE 19 OF APPENDIX C

** SUMMARY FROM TABLE 20 OF APPENDIX C

yielded the results of Table 11. The approximate component concentration of the compressed air used in the PPR was 19 to 23% oxygen (O_2) and 77 to 81% nitrogen (N_2). The expected results would be increased N_2 and CO_2 and decreased O_2 between influent and effluent gas samples.

TABLE 11. PPR OFF GAS ANALYSIS

	% BY VOLUME
Nitrogen	79.2
Oxygen	17.9
Argon	0.9
Carbon Dioxide	2.1
	100.1%

No organic components were detected in the vapors above 5 mg/ℓ. Volatile acids analysis of the liquid portion of effluents from two LBR runs yielded the results in Table 12. Although the influent values are not known and these tests are not conclusive, the higher values for acetic acid over the other volatile fatty acids indicate that some of the residual wet oxidation end products are acetate compounds.

TABLE 12. LBR EFFLUENT VOLATILE ACIDS DATA

RUN CONDITIONS	VOLATILE ACIDS, mg/ℓ*	VOLATILE FATTY ACIDS, mg/ℓ			
		ACETIC	ISOBUTYRIC	BUTYRIC	PROPIONIC
30 MIN/480^{0}F	42	86	ND	ND	7.5
30 MIN/440^{0}F	84	42	ND	ND	ND

* Distillation Method

ND - Not Detected above 10 mg/ℓ.

SECTION 4

COMPUTER SIMULATION OF THE VERTICAL TUBE REACTOR PROCESS

Computer simulation of the VTR process is an important tool for designing full scale facilities. In this Section the models are described and their correlation with pilot plant data is presented. The design of a VTR is assisted by three computer models. The hydrodynamic program calculates flowrates, pressures, and mechanical work done as the liquid and gas flow through the reactor. Two thermodynamic models determine if the reactor will be thermally self-sufficient. The first calculates the heat energy flushed out of the well in the effluent; the other simulates the heat flow to the surrounding earth.

THE HYDRODYNAMIC MODEL

The hydrodynamic computer program simulates the flow of the liquid-air mixture through the reactor. Given a set of initial conditions an element of fluid is followed as the depth and temperature change. The continuously changing conditions, as the element of fluid passes through the reactor, are approximated in the calculation by the finite-element method. (17)

As influent waste flows down the reactor the temperature increases as well as the pressure. The temperature increases according to a temperature profile for the reactor, specified in the input parameters. The pressure is increased because of the added weight of the fluid above. The total pressure increase is reduced slightly because of the frictional loss due to the flow.

At a specified depth and pressure, air is injected into the liquid. This air is compressed and absorbed into the liquid as the pressure increases. The air is compressed according to the ideal gas law. Empirical data for oxygen, nitrogen, and water are used to determine absorption.

The gas and liquid mixture is followed to the reactor bottom where the direction of flow is reversed. Now the pressure and temperature are decreasing as the mixture progresses. The composition of the gas is assumed to remain the same during the flow through the reactor and the properties of the liquid are assumed to be the same as water.

The following input parameters describe the VTR and a specific set of initial conditions for operation.

- VTR Physical Dimension (depth, pipe sizes, surface roughness)
- Wellhead Pressure and Flowrate
- Air Injection Depth and Flowrate
- Temperatures (Wellhead, Transition Zone, Well Bottom)
- Influent Waste COD Level and Reduction Data
- Calculation Parameters
- Influent Pump and Air Compressor Characteristics
- Reaction Zone Length
- Dimension of VTR Heat Exchange System and Heat Exchange Fluid Flowrate

Using these parameters the flow is followed through the reactor and the following calculations are printed at specified intervals.

- Temperature (Following Specified Profiles)
- Pressure
- Vapor Pressure (of water) at that Temperature
- Gas Volume Fraction
- Liquid Velocity
- Frictional Loss
- Time to Reach that Location

In addition there are several calculations made at the end of a hydrodynamic VTR simulation.

- Air Compressor Horsepower
- Influent Pump
- Total Reaction Time
- Total Residence Time in Reactor

. Minimum Difference Between Pressure and Vapor Pressure

. Total Heat Energy Produced During the Reaction

. Total Pressure Drop through Heat Exchange System.

THE HEAT LOST TO EFFLUENT MODEL

This model is used in determining whether or not a VTR design, operating under specified conditions, will be thermally self-sufficient. The two flow sections for the gas and liquid mixture form a single-pass, counter-flow heat exchanger. The influent flow down gains heat energy from the hotter effluent flowing up. The model estimates the energy flushed out in the effluent by calculating a temperature difference between the effluent and influent, the smaller the difference, the more complete the heat exchange.

The model uses the following input parameters, most of which are results of the hydrodynamic computer model.

. Flowrate of Influent

. Flowrate of Effluent

. VTR Physical Dimensions

. Temperature Profile

. Thermal Conductance of VTR Pipe

. Gas Volume Fraction

The results of the calculation are

. Temperature Difference Between Effluent and Influent

. Total Heat Energy, Lost to Effluent.

THE HEAT LOST TO SURROUNDING EARTH MODEL

A significant amount of heat energy is lost by conduction from the hot VTR to the cooler earth surrounding the VTR. This loss is especially important in smaller reactors where less heat is generated by oxidation of the waste. The time when the loss is greatest is in the early stages of operation. At this time

the temperature difference between the reactor and the earth is greatest. The heat loss continually decreases during operation as the surrounding earth rises in temperature and insulates the VTR.

This heat loss by conduction is modeled by assuming the loss is from a long insulated cylinder at a spcified temperature, to a homogeneous, infinite medium. The cylinder temperature is varied in time to approximate a gradual heating of the VTR. The heat flow at this time sets a lower limit on the size of the heat exchange system.

The heat loss to the surrounding earth model requires the following input parameters.

- VTR Physical Dimensions
- VTR Temperature (as a function of time)
- Initial Temperature of the Earth
- Thermal Properties of the Surrounding Earth
- Insulation Properties.

The results of the calculation are

- Temperature Change in the Surrounding Earth
- Heat Flow from the VTR as a Function of Time.

CORRELATION OF COMPUTER MODELS WITH PILOT PLANT DATA

The following correlations of the models with the pilot plant data are made to support the results of the next section, the full scale design. Once a wastewater is shown to be treatable, extensive computer modeling is used to find an efficient VTR. The accuracy of cost comparisons between the VTR and other processes for the treatment of wastewaters, is directly influenced by the accuracy of the computer simulations.

The pilot plant data that is correlated with the models is listed in Appendix E. For each of the operating conditions tabled the reactor remained in nearly the same state. The pressures, temperatures and flow rates remained nearly constant for a period at least as long as the residence time. The tabulation is described further in the beginning of Appendix E.

The hydrodynamic model is correlated with two of the measured pilot plant pressures. The first is the downhole pressure measured in the downflowing wastewater at a depth of 1,289 feet. The second pressure correlated is that of the reactor effluent at the outlet of the wellhead. Both measured and computed pressures for these two locations are listed in Appendix E.

The operating conditions of the pilot plant have been divided into five categories. These five plant conditions are listed in Table 13. The cold VTR conditions, with and without air, were used for calibration and test of the system. Air was injected at the surface during the month of November, 1980, and at the depth of 140 feet for the remainder of the dates in Appendix E. The cold VTR, with air injection category combines these two air inject arrangements.

The correlation between the measured downhole pressure and the computer calculated pressure shows that the computer model consistently underestimates the downhole pressure. This means that when designing a VTR downhole pressure to surpass a given vapor pressure, the model is conservative.

The correlation between the measured outlet pressure and the computer calculated pressure shows that the computer model overestimates the pressure slightly. For this correlation the difference between measured and computed reactor outlet pressure is divided by the sum of absolute pressure changes throughout the entire reactor which for simplicity is assumed to be 1300 psi. The outlet pressure is less important in the design of a VTR than the downhole pressure.

In Table 14 the correlation between measured and calculated heat lost to the effluent is presented. This heat lost is directly proportional to the difference in effluent and influent temperatures. This temperature difference is correlated for the three hot VTR categories. The model is not expected to simulate the cold VTR with air injection, reveal an important energy balance consideration. The model consistently overestimates the heat lost to the effluent by about forty percent. This factor is taken into account in the full scale plant design.

The data from the pilot plant was not suitable for correlating with the heat lost to the surrounding earth model.

TABLE 13. HYDRODYNAMIC COMPUTER MODEL - PILOT PLANT CORRELATION

PILOT PLANT CONDITION	PRESSURE DOWNHOLE			OUTLET PRESSURE		
	PERCENT DIFFERENCE Δ	ABSOLUTE VALUE OF PERCENT DIFFERENCE $\lvert\Delta\%\rvert$	NUMBER DATA SETS	PERCENT DIFFERENCE Δ	ABSOLUTE VALUE OF PERCENT DIFFERENCE $\lvert\Delta\%\rvert$	NUMBER DATA SETS
COLD VTR, NO AIR INJECTION	2.1	2.1	9	-.99	1.01	16
COLD VTR, AIR INJECTION	4.3	4.5	38	-.63	1.52	45
HOT VTR, NO AIR INJECTION	1.61	1.61	10	-.93	.93	63
HOT VTR, AIR INJECTION AT SURFACE	-	-	0	-.80	.85	29
HOT VTR, AIR INJECTION AT 140 FEET	16.2	16.2	34	1.89	1.89	50

$$\Delta\% = \frac{1}{N} \Sigma \frac{P_{MEAS} - P_{COMP}}{P_{MEAS}}$$

$$|\Delta\%| = \frac{1}{N} \Sigma \left| \frac{P_{MEAS} - P_{COMP}}{P_{MEAS}} \right|$$

$$\Delta\% = \frac{1}{N} \Sigma \frac{P_{MEAS} - P_{COMP}}{1300 \text{ PSI}}$$

$$|\Delta\%| = \frac{1}{N} \Sigma \left| \frac{P_{MEAS} - P_{COMP}}{1300 \text{ PSI}} \right|$$

N - TOTAL NUMBER OF DATA SETS, MEAS - MEASURED, COMP - COMPUTER CALCULATED

TABLE 14. HEAT LOST TO EFFLUENT MODEL - PILOT PLANT CORRELATION

ΔT = EFFLUENT TEMPERATURE - INFLUENT TEMPERATURE (F)

PILOT PLANT CONDITIONS	PERCENT DIFFERENCE $\Delta\%$	ABSOLUTE VALUE OF PERCENT DIFFERENCE $\lvert\Delta\%\rvert$	NUMBER DATA SETS
HOT VTR, NO AIR INJECTION	- 3.2	9.6	63
HOT VTR, AIR INJECT AT SURFACE	-40.0	40.0	29
HOT VTR, AIR INJECTION AT 140 FEET	-36.0	38.0	50

$$\Delta\% = \frac{1}{N} \Sigma \frac{\Delta T_{MEAS} - \Delta T_{COMP}}{T_{MEAS}}$$

$$\lvert\Delta\%\rvert = \frac{1}{N} \Sigma \left| \frac{\Delta T_{MEAS} - \Delta T_{COMP}}{\Delta T_{MEAS}} \right|$$

N = TOTAL NUMBER OF DATA SETS, MEAS = MEASURED, COMP = COMPUTER CALCULATED

SECTION 5

FULL SCALE DESIGN

DESIGN GOALS

The most important difference between the design of a VTR waste treatment facility, and a conventional waste treatment facility is the reactor well. The well must be drilled and cased, so both the diameter and depth of the well influence cost of the facility.

Another design goal is to minimize the capital cost and the operating cost of the reactor influent pump and the air compressor. These two systems account for most of the operating cost and are significant in the total facility cost. There is a trade-off between the higher cost of a deeper well, which would reduce the demand on the pumps, and a shallower well needing more expensive pumps.

It is desirable that the VTR be thermally self-sustaining or nearly so. This means that the loss of heat from the VTR is less than the heat generated by the oxidation of the waste. Heat is lost from the VTR by conduction to the surrounding rock and by flushing out heat in the effluent.

A fourth goal is to achieve the maximum waste reduction. In general, both higher reaction times and higher downhole temperatures contribute to better oxidation. In the VTR these are accomplished by deeper wells and lower waste flowrates. Higher temperatures necessitate deeper wells because the greater downhole pressure must be achieved by the column of liquid. The deeper wells increase the facility cost as does the lower flowrates since more reactors will be needed to handle the amount of waste. In designing VTR facilities the COD reduction is used as a measure of the effectiveness of the VTR waste reduction process. The units of COD are mg per liter.

FULL SCALE PLANT DESCRIPTION

A full scale plant is currently under construction at

Longmont, Colorado, located thirty miles north of Denver. The quantity of sludge to be processed in the VTR unit is based on Longmont primary clarifier sludge data which indicates that the needed capacity is 12,500 lb COD/day. The total plant flow at this capacity is 7.5 mgd. The current Longmont waste treatment plant has in line twenty-four hours flow equilization, primary clarifiers, sludge thickeners, anerobic digesters, trickling filters and rotating bio-disks for secondary treatment.

The full scale VTR is described in Table 15. The air and liquid properties are listed first, followed by the thermal characteristics. The reactor dimensions are at the bottom of the table. A COD reduction of 75 percent has been projected from recent LBR data. The data was taken at similar reaction times (34 minutes) and similar maximum temperatures (575^0F).

Figure 16 shows the theoretically predicted, required operating wellhead pressure, plotted as a function of liquid flowrate, for four different given reacted COD concentration levels. Reaction time, i.e. liquid residence time in the reaction zone as previously defined, is also predicted as shown for each given set of flowrates and COD's reacted.

Note that oxygen concentration added at the wellhead is defined as equal to COD reacted concentrations.

The line labeled "Longmont Capacity" is simply the required total pounds of COD to be reacted by the Longmont VTR Plant. Thus as the COD concentration is reduced, an increased flowrate is required.

Any operating point on the Longmont capacity curve will meet the design capacity for the VTR. Once the plant is in operation the optimal flowrate and concentration will be found. The pumping requirements are highest at low flowrates and high COD concentrations, but the heat energy lost to the effluent is lowest. At low concentrations and high flowrates the pumping requirements are lowest, and more heat is lost to the effluent.

ENERGY BALANCE OF FULL SCALE PLANT

The VTR wet oxidation process is unique in that it can produce more energy than it consumes. What makes this possible is the heat energy released when the sludge is oxidized (approximately 6,000 BTU/lb of oxygen consumed) and efficient heat recovery inherent in the system. The heat of oxidation listed in Table 15 assumes that 75% of the 12,500 lb COD/day design load is reduced. The heat flushed is calculated by a computer model. The third heat energy figure in Table 15, the

TABLE 15. LONGMONT FULL SCALE VTR DESCRIPTION

COD CONCENTRATION INFLUENT, (mg/ℓ)	9,300
FLOW, (gpm)	112
REACTOR BOTTOM TEMPERATURE, (^{0}F)	575
COD REDUCTION, (%)	75
REACTION TIME, (min.)	34
OXYGEN INFLUENT, (lb O_2/day)	12,500
AIR COMPRESSOR SHAFT HORSEPOWER	130
INFLUENT PUMP SHAFT HORSEPOWER	35
AIR INJECT PRESSURE, (psia)	500
HEAT OF OXIDATION AT 6,000 BTU/lb COD, (MILLION BTU/hr)	2.36
FLUID ENTHALPY OUT MINUS FLUID ENTHALPY IN (MILLION BTU/hr)	.71
HEAT LOST TO ROCK AFTER 100 DAYS, (MILLION BTU/hr)	.88
REACTOR DEPTH, (ft.)	5,200
HEAT EXCHANGE SYSTEM OD (IN)	4.760
DOWNCOMER FLOW SECTION ID (IN)	5.000
OD (IN)	6.760
UPCOMER FLOW SECTION ID (IN)	7.000
OD (IN)	9.386
WELL SIZE OD (IN)	17.5

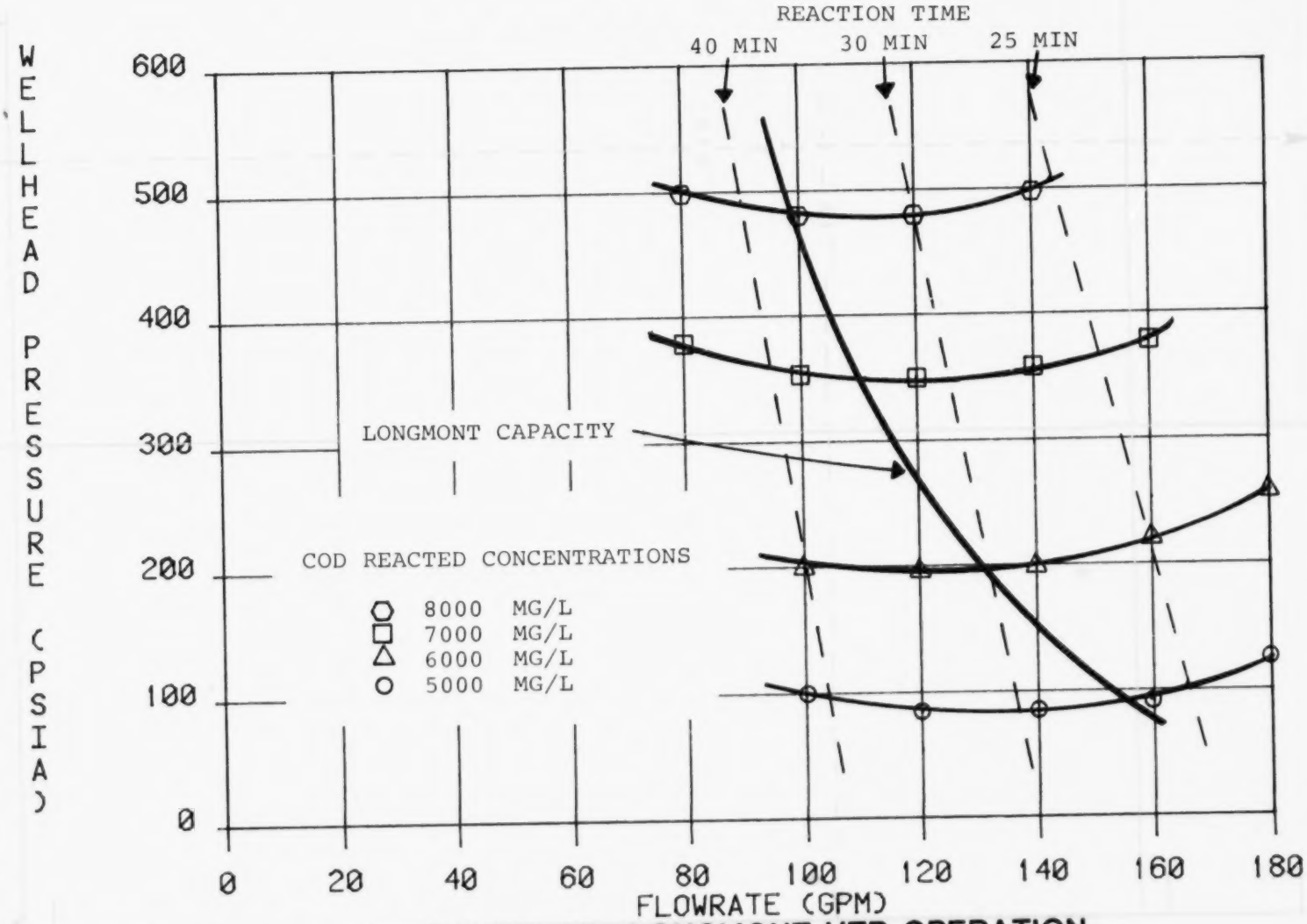

FIGURE 16. LONGMONT VTR OPERATION

heat lost to the rock is taken from Figure 17. The figure shows a loss of 0.88 MILLION BTU/hr for an insulated well with a rock conductivity of 0.6 BTU/hr-ft-^{0}F after a period of 100 days. The total heat energy generated is then

2.36 MILLION BTU/hr
- .71 MILLION BTU/hr
- .88 MILLION BTU/hr

.77 MILLION BTU/hr.

This amount of heat generated can be compared with the power used by the air compressor and influent pump which make up most of the electrical power demand.

130 Air Compressor Shaft Horsepower
+ 35 Influent Pump Shaft Horsepower

165 Total Horsepower = 0.42 MILLION BTU/hr.

This same energy balance has been calculated for each of the points shown in Figure 16. The results are listed in Table 16. The value for Q_{power}, the equivalent power used by the air compressor and the influent pump, will be somewhat higher in the full scale plant due to additional electrical demands. The final figure, ΔQ, is positive for net energy generation and negative for net heat loss. Also, this balance does not take into account the thermal inefficiency in converting the heat produced by the VTR to mechanical or electrical power.

CAPITAL COSTS, AND OPERATION AND MAINTENANCE COST OF FULL SCALE PLANTS

Projected capital costs for four different size VTR facilities are listed in Table 17. The VTR unit size is not limited to the sizes shown. These sizes were selected for convenience and ease of reference with the data developed for the Longmont VTR system. The capital costs have a range which includes the differences in site geology (affecting well drilling costs), construction cost differences across the country and the need in some cases to include additional biological treatment for sidestreams. The projected operation and maintenance costs are also listed in Table 17.

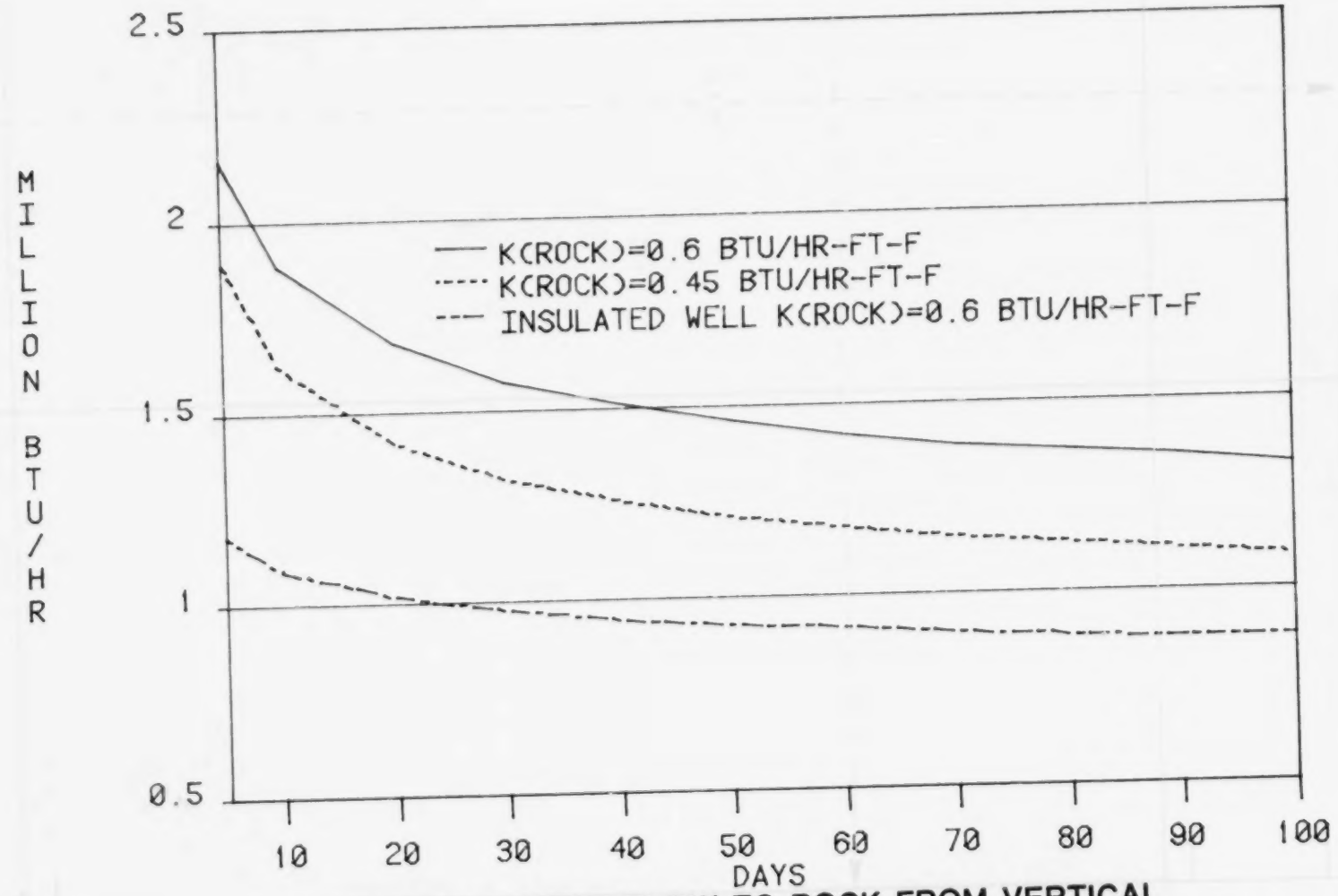

FIGURE 17. HEAT FLOW TO ROCK FROM VERTICAL TUBE REACTER

TABLE 16. FULL SCALE PLANT ENERGY BALANCE

COD (mg/ℓ)	(gpm)	Q_{GEN}	Q_{FLUSH}	Q_{ROCK}	Q_{POWER}	ΔQ
			(MILLION BTU/HR)			
8000	80	1.92	.34	.88	.39	.31
	100	2.40	.64	.88	.46	.42
	120	2.88	.83	.88	.55	.62
	140	3.36	.83	.88	.64	1.0
7000	80	1.68	.44	.88	.32	.04
	100	2.10	.62	.88	.38	.22
	120	2.52	.82	.88	.45	.37
	140	2.94	1.02	.88	.52	.52
	157	3.30	1.21	.88	.59	.62
6000	100	1.80	.59	.88	.30	.03
	120	2.16	.78	.88	.36	.14
	140	2.52	.99	.88	.42	.23
	157	2.83	1.17	.88	.47	.31
	180	3.24	1.43	.88	.55	.38
5000	100	1.50	.56	.88	.24	-.18
	120	1.80	.74	.88	.28	-.10
	140	2.10	.93	.88	.33	-.04
	157	2.36	1.13	.88	.38	-.03
	180	2.70	1.32	.88	.43	.07

TABLE 17. ESTIMATED CAPITAL COSTS, AND OPERATION AND MAINTENANCE COSTS FOR VTR FACILITIES

W.W.T.P. SIZE (MGD)	VTR[1] UNIT SIZE (MGD)	REACTOR DIAMETER (INCHES)	NUMBER UNITS	CAPITAL COST[2] ($1,000,000)
7.5	7.5	8	1	2.0- 3.0
15.0	7.5	8	2	4.0- 6.0
30.0	15.0	12	2	8.0-12.0
100.0	33.0	16	3	25.0-30.0

OPERATION & MAINTENANCE COST/YEAR

W.W.T.P. SIZE (MGD)	ELECT. ($1,000)	DISPOSAL OF ASH ($1,000)	CHEMICAL[3] USE ($1,000)	LABOR ($1,000)	SUPPLIES, MAINTENANCE ($1,000)	TOTAL ($1,000)
7.5	36	3	40	51	24	154
15.0	72	4	80	62	48	266
30.0	140	8	160	70	60	438
100.0	460	20	530	170	180	1,360

1 VTR UNIT SIZED TO TREAT ALL THE SLUDGE FROM THE W.W.T.P.

2 ESTIMATES BASED ON 5,000-6,000 FOOT DEEP REACTOR-600 F MAXIMUM TEMPERATURE AND 70% COD REDUCTION. THE CAPITAL COST SHOULD BE SUFFICIENT TO COVER THE COST OF CONSTRUCTING ADDITIONAL BIOLOGICAL TREATMENT FOR VTR EFFLUENT IF NECESSARY, AND TO COVER COSTS OF DIFFERENT DRILLING SITUATIONS.

3 NITRIC ACID

NOTE: COSTS PRESENTED ON THIS PAGE ARE FOR PLANNING PURPOSES ONLY, AND ARE NOT TO BE USED FOR QUOTATION.

REFERENCES

1. Applied Science & Engineering, Inc., Municipal Sludge Disposal by use of the Vertical Tube Reactor (VTR). McGrew, J. L., Englewood, Colorado, 1978. (Available through author).

2. Municipal Sludge Disposal by Vertical Tube Reactor Process. EPA Contract 68-03-2812, June 6, 1979.

3. Municipal Sludge Disposal by Vertical Tube Reactor Process, Monthly Report. U.S. Environmental Protection Agency Contract No. 68-03-2812, Cincinnati, Ohio, July 1979 to April 1980.

4. Municipal Sludge Disposal by Vertical Tube Reactor Process, Interim Report. U.S. Environmental Protection Agency Contract No. 68-03-2812, Cincinnati, Ohio, October 1980.

5. McGrew, J. L., et.al., Wet Oxidation of Municipal Sludges by Vertical Tube Reactor (VTR), Unpublished Drafts. Cincinnati, Ohio, 1980-1981.

6. McCarthy, J.J., Technology Assessment of the Vertical Well Chemical Reactor. EPA-600/2-82-005, Municipal Environmental Research Laboratory, Cincinnatti, Ohio, February 1982.

7. McGrew, J.L., et.al., Design of a Pilot Vertical Tube Reactor for Industrial Waste Disposal, Unpublished Report, Applied Science & Engineering, Inc., Englewood, Colorado, 1976. (Available through author).

8. Nielson, D.H. and Jacknam, A. L., A Metallurgical Examination of VTR Welded Tubing. Biomaterials Research Institute, Slat Lake City, Utah, January 1980.

9. Knopp, P. V. and Wilhelmi, A. R., Wet Air Oxidation-An Alternative to Incineration. Chem. Engr. Progress, August 1979.

10. Sundstrom, D. W. and Klei, H.E., Wastewater Treatment. Prentice-Hall, Inc., Englewood Cliff, N.J., 1979, pp. 392-397.

11. Teletzke, G., Gitchell, W., Diddams, D. and Hoffman, C., Components of Sludge and its Wet Air Oxidation Products. Journal WPCF, 39(6):994-1005, 1967.

12. Tchobanoglous, G., Wastewater Engineering:Treatment, Disposal and Reuse. Metcalf & Eddy, Inc., Boston, 1979, pp. 744-751.

13. Sundstrom, ibid., p. 28.

14. Applied Science & Engineering, Inc., Deposit Analysis, Vertical Tube Reactor Corporation. Unpublished Report, March 24, 1982.

15. Sundstrom, ibid., p. 19.

16. Tchobanoglous, ibid., pp. 258-276.

17. Dahlquist, G. and Bjorck, A., Numerical Methods, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1974.

APPENDIX A

THE PPR FACILITY

INTRODUCTION

Located at an abandoned oil well 25 miles east of Denver, Colorado, the Pilot Plant Reactor (PPR) was the first operating model of a Vertical Tube Reactor. The reactor itself is described in the body of this report. This Appendix describes the surface facility provided to operate and control the reactor and provides a summary of PPR operating procedures.

The PPR, designed and built by Applied Science & Engineering, Inc., Englewood, Colorado, during 1976 and 1977, was first operated in the Fall of 1977. During its 3-1/2 year life, the PPR was modified frequently and extensively as the result of both operating problems and design improvement. These changes are treated briefly in Section 2 of this report.

The facility was last operated in March, 1981, and after salvage, was abandoned, having made major contributions to the knowledge of operating and performance characteristics of this unique means for wastewater treatment.

FACILITY DESCRIPTION

A pictorial description of the PPR topside facility is shown in Figures A-1, 2, 3, and 4.

Figure A-1 shows the general arrangement of the surface structure with the sludge storage tank to the left of the process equipment building and the reactor service derrick atop the control room on the right. In Figure A-2, an interior view of the control room, the wellhead is in the foreground with the instrumentation and control panel in the rear. In the process equipment room, Figure A-3, the air compressor is on the left, and the sludge pump is in front of the sludge storage tank. The effluent tank, as seen in Figure A-4 is to the right of the sludge storage tank.

The floor plan layout of the PPR facility is presented by Figure A-5. Figure A-6 shows the process piping and control schematic arrangement.

OPERATION

A major factor affecting PPR operation and data collection was the location of the plant. Dictated by the closest available abandoned oil well large enough to contain the reactor, the remote location of the site, distance (40 kilometers) from the nearest sewage treatment plant, lack of water and limited accessibility during winter weather conditions were accpeted from the outset as presenting operating restrictions. The extent of the consequent problems however, was well beyond initial expectations, necessitating expenditures of time, manpower and dollars to the point of reducing the amount of information obtained from this project on plant performance.

CONTROL AND INSTRUMENTATION

The PPR was initially designed to test the VTR concept and to gain knowledge on control of the process. Since it was expected that the facility would be modified throughout its life manual controls and data taking methods were chosen. Operators were required to record all data such as flow rates, temperatures, and pressures, and all operating information on daily log sheets. It is estimated that from 30 to 60 percent of their time during test runs was used for this purpose. A sample log sheet is included here as Figure A-7.

The reactor control system depended on the operator for essentially all feedback controls, an intended feature of the design to allow determination of the relationships and sensitivities of the process elements and selection of effective sequences for process control.

SAMPLING PROCEDURES

Sampling of reactor influent and effluent was accomplished manually at the site by taking grab samples. Composite samples were made up of individual samples taken during steady state conditions. It was observed after considerable sampling that even though the reactor influent strength was fairly uniform the only way to obtain consistent results was to take numerous influent and effluent samples over a comparatively short period of time.

Reactor influent samples were taken at the reactor "Christmas Tree", the point where the reactor enters the well casing. Reactor effluent was sampled from the surface of the first compartment of the reactor effluent tank. At this point the sludge and dilutant water were well mixed due to the agitation of the water as the nitrogen, carbon dioxide and unused oxygen were liberated.

Coordination of influent and effluent sampling was effected by sampling the effluent at a time delay after influent sampling equal to the computed reactor flow through time. Normal procedure was to take six influent samples, one every ten minutes for one hour. Six effluent samples were then taken every ten minutes for an hour, starting at the computed time delay after the first influent sample was taken.

Samples of the sludge delivered to the test site were taken when the sludge was picked up at the wastewater plant, and again after being pumped into the sludge storage tank.

Since the test facility was not located at a MWWTP, storage tanks were used for holding sludge and dilution water. This design allowed the operator to adjust reactor influent feed strength to hold the reactor effluent dissolved oxygen (D.O.) above 1.0 mg/liter.

Since the sludge pump flowrate was adjustable only over a narrow range (.5-1.0 gpm) the sludge in storage was in fact diluted sufficiently to place the sludge flow rate within that range. Early in the program raw sludge had been hauled to the pilot plant for testing purposes. Though mixing in the storage tank was limited, the sludge was being digested in the tank so quickly that it was difficult keeping the reactor influent COD strength near desired values. Consequently all sludges used in the pilot plant test program in 1980 and 1981 were digested sludges. These sludges did not experience any significant deterioration in strength over time and enabled reactor influent COD loadings to remain more uniform.

During the test runs in August and September, 1980, variations in strength of the stored sludge due to stratification were noted. After installation of two propeller type mixers in the storage tank variations over time were negligible.

Sludge hauled to the site was transported in a 1,500 gallon tank truck and off loaded via a trash pump to the sludge storage tank. Design limitations of the truck trash pump limited sludge solids concentrations to approximately 2.0% by weight. Since this truck also was used to haul dilutant water it was necessary to rinse the tank before hauling.

Since the testing protocol set for the PPR was to operate at a constant organic loading rate and flow rate, once the flow rate and operating pressure were selected, the main feed pump, a progressing cavity type, was operated at constant speed resulting in a nearly constant flow rate through the reactor. Control of reactor influent strength was effected by adjusting the quantity of sludge being pumped to the mixing unit by the sludge pump, also a progressing cavity type. Measurements of

the dilutant flow with and without the sludge pump operating were used to calculate the quantity of sludge being processed at any time. A sludge flow meter was also used to check sludge flow. During steady state operations, i.e., constant reactor air flow and reactor influent and effluent pressures, a drop in reactor effluent dissolved oxygen signalled a reduction in sludge flow to the reactor. After one hour if the reactor effluent dissolved oxygen did not increase, the sludge flow would again be reduced a small amount. This continued until the reactor effluent dissolved oxygen was steady and at least one mg/liter.

Air Flow Control

Air to the reactor was provided at a constant flow rate. During start up periods when flow rates through the reactor were being stabilized, air flow would be increased slowly up to a predetermined amount based on an anticipated organic loading to the reactor. Once air flow rate had been established and reactor temperatures were at the desired conditions, sludge would be introduced, and the sludge flow adjusted until the effluent dissolved oxygen was at least one mg/liter or more as described above.

Air flow before March, 1981 tests was monitored with a rotometer. Higher operating pressures during the March, 1981, test required a change to a head meter with pressure differential gauges. A compressor duty cycle meter was used to determine the actual quantity of air to the reactor.

Influent and Effluent Pressure Control

The single device used most frequently to control reactor operation was the reactor effluent control valve. Located on the control console this valve was used to hold the reactor effluent pressure at a predetermined value. During the test periods of August-Decemver, 1980, the reactor influent pressure was normally set at in the 140-160 psi range. At this influent pressure the main feed pump had a very steady flow rate as the pump head curve was quite flat in this region. Consequently the reactor effluent control valve when set, would often not have to be adjusted for eight to twenty-four hours. During the March, 1981, operating period with reactor influent pressures running from 380 to 410 psi the reactor control valve had to be constantly adjusted to keep the influent pressure and hence influent flow constant.

Reactor Temperature Control

The reactor temperature was controlled by varying the rate of flow and temperature of heat exchanger water flowing to the

reactor. In the 1980 test periods heat losses to the rock and to the reactor effluent were such that the maximum deliverable boiler temperature was only 480^{0}F, limiting maximum reactor steady state temperature to 444^{0}F after several days' operation.

In the modifications made for the high temperature and pressure run of March, 1981, the boiler heating capacity and heat exchanger pump capacity were doubled. Boiler output temperatures of 527^{0}F were easily attainable. Consequently, as the heat losses to the rock decreased, the boiler output temperature and flow had to be reduced to keep the reactor from overheating. Because of the heat exchanger pump arrangements (belt and pulley drive), the heat exchanger flow could only be varied at discrete rates of flow. This made smooth control of reactor temperatures difficult at the high temperature regime.

Reactor temperatures were monitored with thermocouples attached to the reactor piping both above and downhole. Failure of some of the downhole thermocouples resulted in having to interpolate for certain of the downhole temperatures. This was accomplished by using a temperature differential correlation based on earlier readings when all thermocouples were operating.

Reactor Effluent Disposal

In the effluent tank, the effluent first entered the bottom of a small vented compartment. Open to the atmosphere, this compartment enabled process gases, mainly oxygen, nitrogen and carbon dioxide to exit from the liquid. The effluent then passed over a weir to a larger compartment, where solids were removed for analysis by both skimming and settlement.

All effluent, after sampling, was collected in a sump where it was pumped out to surrounding grasslands.

The effluent tank described above was not designed to accomplish efficient solids removal, but to allow observation of the reactor effluent before discharge and to facilitate sampling. Based upon observations of the tank performance it appears that either a settling tank or foam separation unit could work equally well in achieving desired solids separation.

Reproduced from
best available copy.

FIGURE A-1 GENERAL ARRANGEMENT OF PPR FACILITY

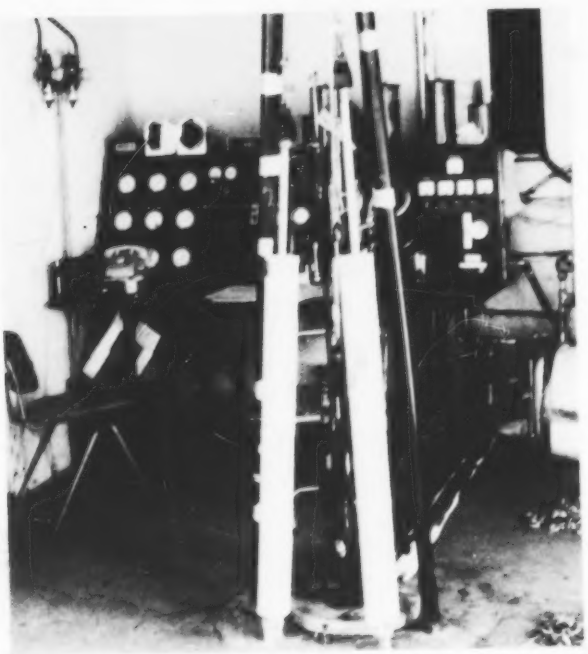

FIGURE A-2 PPR CONTROL ROOM

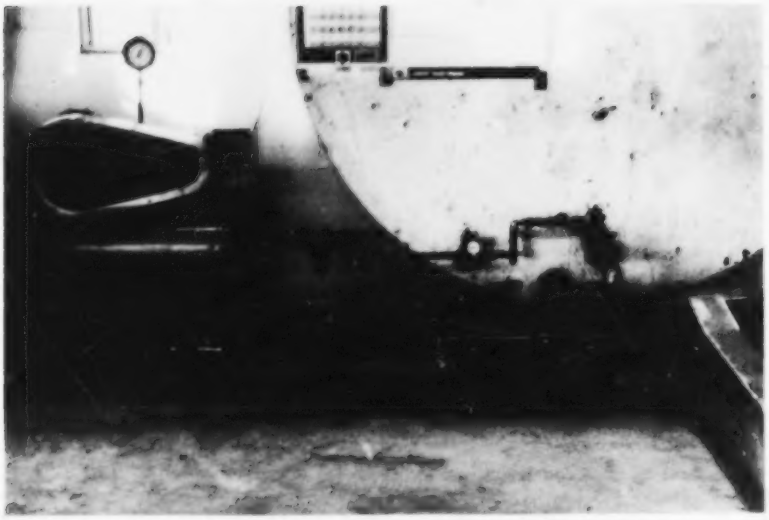

FIGURE A-3 PPR EQUIPMENT ROOM, AIR COMPRESSOR AND SLUDGE PUMP

FIGURE A-4 EFFLUENT TANK

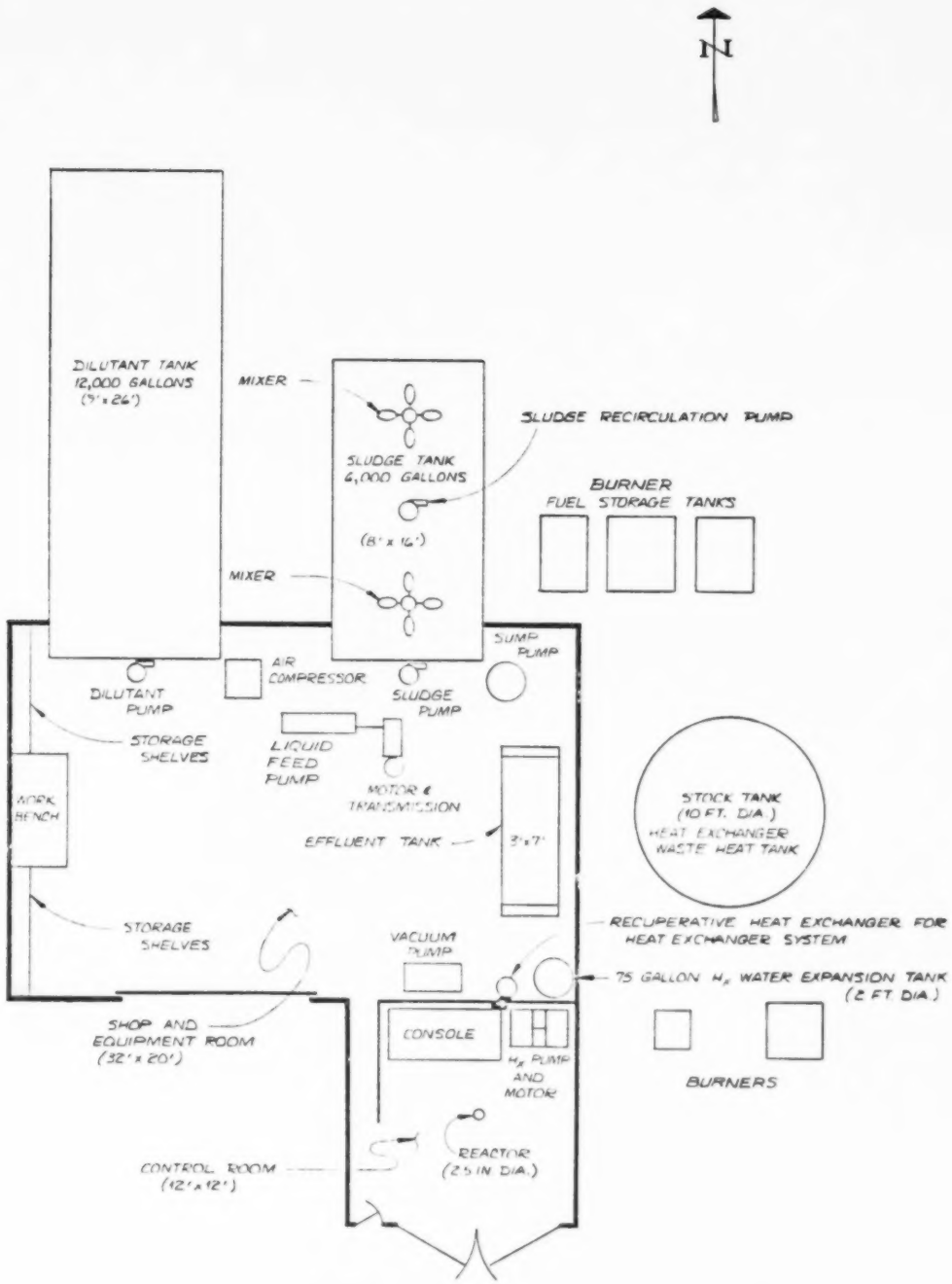

FIGURE A-5. FLOOR PLAN LAYOUT OF THE PPR FACILITY

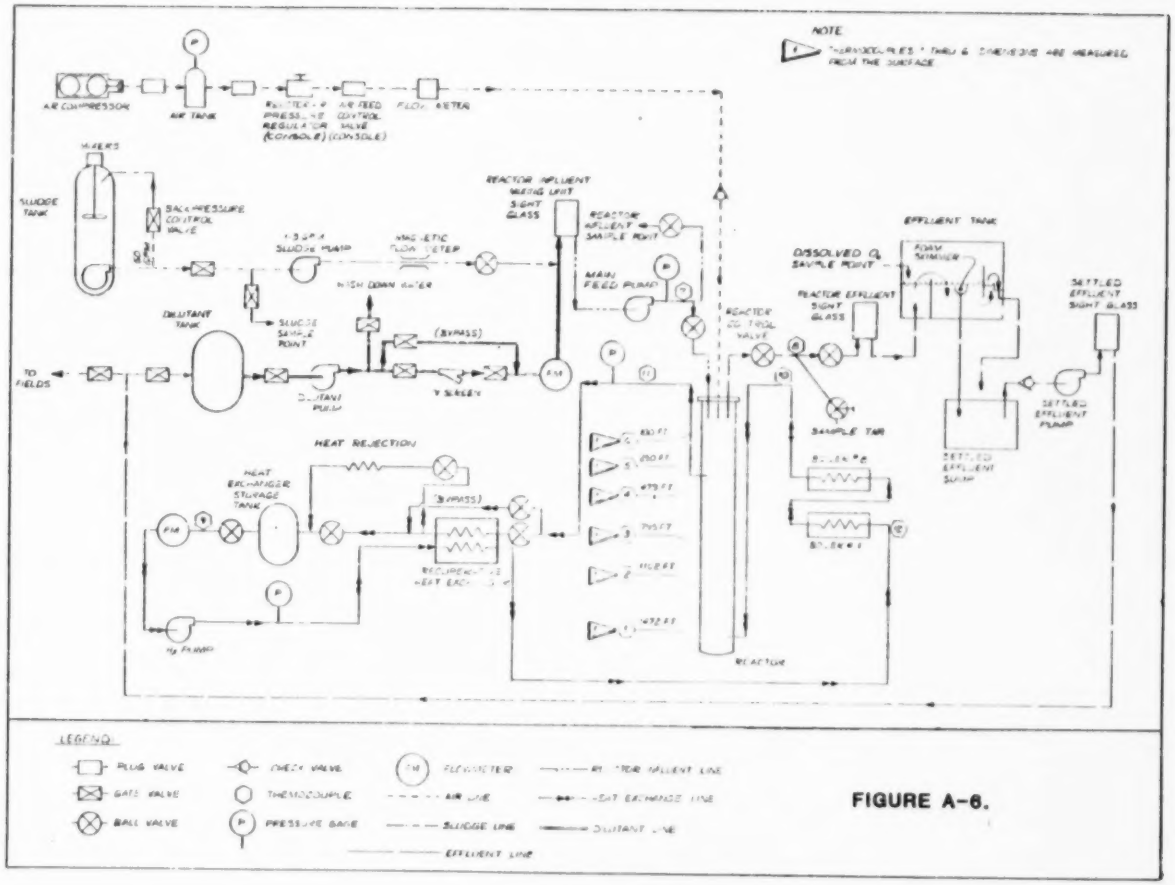
NOTE
AIR COMPRESSOR
AIR TANK
FLOW METER
SLUDGE TANK
BACK PRESSURE CONTROL VALVE
SLUDGE PUMP
MAGNETIC FLOW METER
WASH DOWN WATER
SLUDGE SAMPLE POINT
DILUTANT TANK
(BYPASS)
Y STRAINER
TO FIELDS
REACTOR INFLUENT MIXING UNIT SIGHT GLASS
REACTOR INFLUENT SAMPLE POINT
MAIN FEED PUMP
REACTOR EFFLUENT SIGHT GLASS
SAMPLE TAP
EFFLUENT TANK
FOAM SKIMMER
DISSOLVED O2 SAMPLE POINT
SETTLED EFFLUENT SIGHT GLASS
SETTLED EFFLUENT PUMP
HEAT REJECTION
HEAT EXCHANGER STORAGE TANK
REACTOR
LEGEND
PLUG VALVE
GATE VALVE
BALL VALVE
CHECK VALVE
THERMOCOUPLE
PRESSURE GAGE
FLOWMETER
AIR LINE
SLUDGE LINE
EFFLUENT LINE
HEAT EXCHANGE LINE
DILUTANT LINE

FIGURE A-6.

12-4-80

12:00 noon Run time 11868.6

VTR DATA SHEET

DATE & TIME	TEMPERATURES DEG F												REACTOR									AIR			HEAT EXCHANGER									pH		COMMENTS
	1472 1	1166 2	795 3	479 4	5	6	VTR IN 7	VTR OUT 8	HX SUC 9	HX DIS 10	HX RET 11	BOILER INPUT 12	SLUDGE FLOW GPM	SLUDGE PUMP %	DIL'T. FLOW GPM	T. TAL FLO GPM	V FLC PSI	P IN PSI	P OUT PSI	P BOT. PSI	D.O. OUT MG/L	P IN PSI	F.M. #	V.	HX PUMP FLOW GPM	P COOL PSI	P OUT PSI	P RET PSI	BOILER OIL PRES PSI	SET TEMP °F	D.C. %	OIL FLOW GPH	#FLUE TEMP	IN	OUT	
0931	-	1022	-	92	85	64.0	92.4	55	59	75	65	61	-	-	-	-	-	-	-	-	-		2						515						Pump Starting.
Noon	-	942	-	163	112	93	-	-	94	455	129	135	-	-	-	-	-	-	-	-	-		2					450	570		1310				Started heating 1°55AM
1430	-	956	-	182	135	101			91	457	157	145	-	-	-	-	-	-	-	-	-		2					420	570						2 in 2 out 1 in 1 out.
1530	263	958		188	136	102			91	458	158	146	-	-	-	-	-	-	-	-	-		2		2.7	28	550	90	170	570	100	1457				
19:37	278	993		206	139	104	469	60.3	93	462	1710	1575	0	0	3.2	3.2	112	43	-	-	111	1	-	2.7	29	552	79	170	580	100	1477				Swing boiler flat. Mg° Dan
21:00	310	287		203	138	104							Fire from here down off & on for hour hour for event, shutdown																							
							421	60.0	915	463	170	159	-	-	3.2	3.2	112	42	-	-	111	1		2.7	27	490	90	170	580	109	1444				HX Stuck Shutdown 12:45
12-5-80																																				
0000	346	315	-	218	145	105	502	62	969	466	181	166	-	-	3.2	3.2	1.9	34	-	-	112	1.0		2.7	26	557	99	170			1509	317			TP
0100	342	318	-	221	146	105	504	62.3	973	466	182	167	-	-	3.2	3.2	1.9	34	-	-	113	1.0		2.7	26	557	99	170			1509	315			
0200	342	308	-	225	148	105	504	62.5	974	466	180	170	-	-	3.2	3.2	1.9	33	-	-	112	1.0		2.7	26	554	99	170			1509	309			
0300	337	327	-	227	149	105	505	62.9	974	467	180	170	-	-	3.2	3.2	1.9	33	-	-	112	1.0		2.7	26	556	99	170			1509	320			
0400	338	330	-	230	151	105	506	62.7	976	467	182	173	-	-	3.2	3.2	2.1	39	-	-	112	1.0		2.7	26	561	99	170			1509	321			
0500	345	333	-	232	152	106	507	63.0	978	468	182	178	-	-	3.2	3.2	2.0	35	-	-	112	1.0		2.7	26	561	99	170			1509	324			
0600	369	351	-	235	153	106	508	63.1	979	468	180	174	-	-	3.2	3.2	1.9	34	-	-	113	1.0		2.7	26	563	99	170			1509	327			
0700	371	340	-	237	154	106	510	63.3	978	468	180	175	-	-	3.2	3.2	1.9	31	-	-	111	1.0		2.7	27	564	99	170	580	100	1509	326			
0800	378	372	-	238	154	106	513	63.2	981	469	180	175	-	-	3.2	3.2	1.9	31	-	-	111	1.0		2.7	26	569	99	170	580	100	1509	327			
0930	394	347	-	239	156	104	511	66	988	468	181	175	1.00	50	3.5	4.5	3.5	148	-	7.3	113	3.0		2.7	26	565	99	170	600	100	1549	350			Cut in Sludge 0830 RP
0100	360	345	-	240	155	102	511	64	988	462	182	176	1.0	50	3.6	4.5	4.6	150	-	5.6	150	3.0		2.7	25	565	99	170	600	100	1562	338			
0200	359	346	-	240	155	102	511	65	988	468	182	176	1.0	50	3.5	4.5	4.2	150	-	5.6	150	3.0		2.7	25	565	99	170	600	100		348			
0300	321	324	-	240	153	102	511	65	988	468	182	176	1.0	50	3.5	4.5	4.5	150	-	5.7	150	3.0		2.7	25	570	95	170	600	100	1580	351			
0400	362	345	-	241	162	109	513	71	101	465	184	177	1.0	50	3.5	4.5	4.5	150	-	5.8	150	3.0		2.7	25	565	95	170	600	100	1594	338			
0500	359	344	-	241	158	-	512	70	101	465	180	178	1.0	50	3.5	4.5	4.5	150	-	5.9	150	3.0		2.7	25	565	95	170	600	100	1594	349			
0600	372	345	-	244	159	111	512	68	103	465	181	178	1.0	50	3.5	4.5	4.5	150	-	5.8	150	3.0		2.7	25	565	95	170	600	100	1594	348			Down for 5 mins to
0700		342		243	159	111	512	68.3	104	465	185	178	.2	24	4.3	4.3	45	162		1.0	165	3.0		2.7	22	550	80	170	600	100	1601	350			trigger new pump bolt.
0800		347		246	162	106	512	66.4	104	465	184	178	.4	50	2.6	4.5	50	162		5.1	160	2.0		2.7	22	552	78	170	600	100	1601	347			
0900		347		250	172	107	510	65.9	106	468	201	184	.4	50	3.6	4.5	158	44		4.8	159	2.0		2.7	21	552	77	170	600	100	1608	344			
1000		348		256	174	113	514	65.3	105	469	202	182	.8	48	3.7	4.5	151	45		5.0	152	2.0		2.7	21	552	76	170	600	100	1621	348			Started Unmanned patrol stay
1100		358		254	172	109	504	65.2	107	465	209	181	.8	48	3.2	4.5	158	44		5.0	154	2.0		2.7	25	560	70	170	600	100	1628	347			
1130		352		256	170	110	505	65.2	108	465	205	184	.7	0%	3.8	4.4	160	46		4.1	155	2.0		2.7	24	560	70	170	600	100	1624	344			out water pic 46

FIGURE A-7.

Reproduced from best available copy.

APPENDIX B

DESCRIPTION OF WASTEWATER TREATMENT PLANT FACILITIES

DENVER NORTHSIDE TREATMENT PLANT, DENVER, COLORADO

This plant is a 106 million gallon per day (mgd) primary treatment plant which pumps thickened sludge from primary clarifiers to anaerobic digesters. Digester supernatent is returned to the plant. Sludge from the digesters, containing three to six percent solids, is pumped to the Denver Metro W.W.T.P. for further treatment. The digested sludge samples for this study were taken from the digester feed to the Denver Metro W.W.T.P.

DENVER METRO WASTEWATER TREATMENT PLANT, DENVER, COLORADO

This plant is a 170 mgd activated sludge plant with 70 mgd of primary clarifier capacity.

The secondary system treats the Denver Northside primary clarifier effluent and approximately 70 mgd of raw sewage. The plants secondary system consists of a 70 mgd pure oxygen plant and a 100 mgd air system.

Anaerobic digesters treat a portion of primary clarifier sludge and thickened waste activated sludge. Digested sludge is hauled by tank trucks to a land spreading site. The remaining primary clarifier sludge and waste activated sludge are thickened on vacuum filters with line and ferric chloride and hauled to a same land spreading site. Denver Northside sludge is dewatered on vacuum filters and dried for reuse by the City of Denver on park lands. Significant industrial wastes going to the Denver Metro and Denver Northside facilities include metal plating, food processing and chemical process products. The untreated sludge sample for this study is a blend of primary sludge from the Denver Northside facility and secondary activated sludge from the Denver Metro facility. The sample was collected from the feed into the anaerobic digesters.

LONGMONT WASTEWATER TREATMENT PLANT, LONGMONT, COLORADO

The Longmont Waste Water Treatment Plant (at the time of this study) is a 6 mgd facility with in line flow equalization,

primary clarifiers, roughing filters followed by biodisks and secondary clarification.

Primary sludge is thickened in a gravity thickener and pumped to a two stage anaerobic digester. Secondary digested sludge is hauled in liquid form to the surrounding farm land or dried on site in drying beds. The primary sludge sample was collected from the thickener feed into the digester.

BRUSH WASTEWATER TREATMENT PLANT, BRUSH, COLORADO

The Brush W.W.T.P. is designed for a 1.5 mgd flow and was receiving 0.8 mgd at the time samples were collected for this study. Brush receives 80% of its organic load and 50% of its hydraulic flow from a beef packing plant.

The plant consists of primary clarifiers, two stage trickling filters and secondary clarifiers. Sludge is pumped from the primary clarifiers to a two stage anaerobic digester. Digested sludge is spread on nearby farm land. Sludge samples for this study were collected from the primary clarifier feed to the digester.

AURORA WASTEWATER TREATMENT PLANT, AURORA, COLORADO

This extended aeration activated sludge plant has a flow of 1.5 mgd. The plant is composed of two aeration basins and two clarifiers. There is no primary clarifier and all the sludge is discharged to Denver Metro's interceptor system. Wastes are basically from residential and commercial sources. The domestic waste samples for this study are from secondary clarifier return sludge.

APPENDIX C

LABORATORY BATCH REACTOR TEST REULTS

The following tables present the significant quantitative results of the laboratory reactor tests.

TABLE C-1. LBR TCOD, SCOD, TBOD AND pH DATA FOR DIGESTED SLUDGE, DENVER NORTHSIDE W.W.T.P.

DATE RUN	MAXIMUM TEMPERATURE ^{0}F	REACTION TIME MINUTES	pH IN	pH OUT	TCOD IN mg/ℓ	TCOD OUT mg/ℓ	TCOD RDXN %	SCOD OUT mg/ℓ	SCOD/ TCOD OUT %	TBOD OUT mg/ℓ	TBOD/ TCOD OUT %
1-31-80	400	30	7.8	7.1	2660	2310	13	1560	68	1010	44
1-29-80	500	30	7.6	6.7	2960	1370	54	1230	90	780	57
1-25-80	600	30	7.6	7.5	3040	720	76	713	99	483	67
1-22-80	650	30	7.6	7.0	3210	591	82	564	95	424	72
1-30-80	400	60	7.8	6.8	2630	1710	35	1440	84	859	50
1-28-80	500	60	7.6	6.5	3260	1220	63	1080	89	810	66
1-24-80	600	60	7.6	7.0	3180	655	79	616	94	455	69
1-22-80	650	60	7.6	7.6	3080	530	83	538	102	389	73

TABLE C-2. LBR TCOD, SCOD, TBOD AND pH FOR BLENDED SLUDGE, DENVER NORTHSIDE AND DENVER METRO W.W.T.P.

DATE RUN	MAXIMUM TEMPERATURE ^0F	REACTION TIME MINUTES	pH IN	pH OUT	TCOD IN mg/ℓ	TCOD OUT mg/ℓ	TCOD RDXN %	SCOD OUT mg/ℓ	SCOD/ TCOD OUT %	TBOD OUT mg/ℓ	TBOD/ TCOD OUT %
4-1-80	400	30	7.4	5.7	3230	2360	27	1800	76	1240	53
2-25-80	500	30	6.9	5.0	3520	1690	52	1430	85	1100	65
2-18-80	600	30	6.9	6.6	2810	708	75	748	106	491	69
2-15-80	650	30	7.0	7.0	2820	576	80	576	100	394	68
4-1-80	400	60	7.4	5.7	3230	2020	37	1660	82	1210	60
2-19-80	500	60	7.0	6.7	3100	1100	65	988	90	798	73
2-14-80	600	60	7.0	6.8	2800	616	78	648	105	440	71
4-3-80	650	60	6.6	6.0	2520	478	81	506	106	340	71

TABLE C-3. LBR TCOD, SCOD, TBOD AND pH PRIMARY SLUDGE, LONGMONT W.W.T.P.

DATE RUN	MAXIMUM TEMPERATURE ^0F	REACTION TIME MINUTES	pH IN	pH OUT	TCOD IN mg/ℓ	TCOD OUT mg/ℓ	TCOD RDXN %	SCOD OUT mg/ℓ	SCOD/ TCOD OUT %	TBOD OUT mg/ℓ	TBOD/ TCOD OUT %
10-15-80	400	30	5.7	3.9	3057	2770	9	1580	57	596	22
10-1-80	500	30	5.5	4.1	2260	1140	50	1060	93	NR	-
10-8-80	600	30	5.6	4.8	2840	1060	63	694	65	739	70
10-8-80	650	30	5.6	4.8	3160	830	74	570	69	584	70
10-17-80	400	60	5.6	NR	2830	NR	-	1736	-	NR	-
10-17-80	500	60	5.7	NR	3320	1570	53	NR	-	878	56
10-17-80	600	60	5.5	4.8	2560	781	69	708	91	593	76
10-16-80	650	60	5.6	5.0	3130	699	78	392	56	557	80

NR - NOT RUN

TABLE C-4. LBR TCOD, SCOD, TBOD AND pH PRIMARY SLUDGE WITH FOOD PROCESSING WASTE, BRUSH W.W.T.P.

DATE RUN	MAXIMU TEMPERATURE ^0F	REACTION TIME MINUTES	pH IN	pH OUT	TCOD IN mg/ℓ	TCOD OUT mg/ℓ	TCOD RDXN %	SCOD OUT mg/ℓ	SCOD/ TCOD OUT %	TBOD OUT mg/ℓ	TBOD/ TCOD OUT %
10-24-80	400	30	5.2	4.0	2980	2350	21	1590	68	1000	43
10-24-80	500	30	5.8	4.8	2120	1690	20	1410	83	1220	72
10-25-80	600	30	6.0	4.8	1630	402	75	NR	-	375	93
10-27-80	650	30	5.7	5.1	2930	405	86	287	71	300	74
10-27-80	400	60	5.5	4.1	2960	2510	15	1700	68	2000	80
10-25-80	500	60	5.6	4.4	2970	NR	-	1135	-	1600	-
10-25-80	600	60	6.0	5.0	1740	686	61	683	100	622	91
10-26-80	650	60	5.3	5.0	1770	360	80	161	45	450	125

NR - NOTE RUN

TABLE C-5. LBR TCOD, SCOD, TBOD AND pH DATA FOR DOMESTIC WASTE, AURORA W.W.T.P.

DATE RUN	MAXIMUM TEMPERATURE ^0F	REACTION TIME MINUTES	pH IN	pH OUT	TCOD IN	TCOD OUT mg/ℓ	TCOD RDXN %	SCOD OUT mg/ℓ	SCOD/ TCOD OUT %	TBOD OUT mg/ℓ	TBOD/ TCOD OUT %
9-30-80	400	30	6.0	5.6	2840	2000	30	1950	98	1220	61
9-11-80	500	30	5.5	6.2	3200	1780	44	1320	74	725	41
10-1-80	600	30	6.0	5.5	2820	1420	50	713	50	641	45
10-2-80	650	30	6.0	6.4	2860	745	74	729	98	557	75
9-12-80	400	60	5.9	4.6	2820	2360	16	1580	67	NR	-
9-11-80	500	60	5.6	5.4	2850	1270	55	NR	-	758	60
9-10-80	600	60	5.7	6.6	2920	870	70	471	54	594	68
12-3-80	650	60	5.6	6.8	3100	702	77	NR	-	534	76

NR - NOT RUN

TABLE C-6. SUMMARY OF LBR COD REDUCTION DATA FOR VARYING REACTION TIMES AND TEMPERATURES*

REACTION TEMPERATURE ^0F	REACTION TIMES, MINUTES					
	120	60	45	30	20	15
400	-	26.0 ± 11.9%	-	26.7 ± 9.7%	-	-
445	-	-	-	35.9 ± 14.0%	24.6 ± 6.3%	21.4 ± 2.0%
450	-	-	75.7%	-	-	-
460	-	-	-	-	24.9%	-
500	-	58.8 ± 5.6%	-	47.2 ± 10.1%	-	-
525	77.3%	73.2 ± 4.6%	-	-	-	-
550	61.7%	57.6%	-	56.4 ± 9.1%	-	-
575	80.9%	77.4 ± 2.8%	-	59.7 ± 8.1%	-	-
600	81.1 ± 14.0%	73.9 ± 9.4%	-	70.5 ± 9.4%	-	74.1%
625	-	-	65.3 ± 3.8%	69.2 ± 1.2%	-	-
650	79.9 ± 4.6%	79.4 ± 12.6%	73.8 ± 5.2%	75.8 ± 6.3%	-	-
680	88.6%	91.4 ± 8.1%	-	-	-	-

* AVERAGES OF DATA CONTAINED IN TABLES 7 THROUGH 12 OF THIS APPENDIX.

TABLE C-7. LBR DATA FOR TWO HOUR REACTION TIMES

DATE RUN	REACTION TEMPERATURE ^0F	INITIAL PRESSURE psig	TCOD INFLUENT mg/ℓ	TCOD EFFLUENT mg/ℓ	TCOD REDUCTION %
3-10-80	525	110	1467	333	77.3%
3-19-80	550	80	698	267	61.7%
3-11-80	575	110	1364	260	80.9%
7-10-79	600	80	454	41	91.0%
3-20-80	600	80	668	192	71.2%
					81.1% ± 14.0%
3-12-80	650	110	1376	203	85.2%
3-20-80	650	80	698	157	77.5%
3-28-80	650	80	488	112	77.0%
					79.9 ± 4.6%
3-6-80	680	110	1628	186	88.6%

TABLE C-8. LBR DATA FOR SIXTY MINUTE REACTION TIMES

DATE RUN	REACTION TEMPERATURE ^0F	INITIAL PRESSURE psig	TCOD INFLUENT mg/ℓ	TCOD EFFLUENT mg/ℓ	TCOD REDUCTION %
1-30-80	400	180	2630	1710	35.0
4-1-80	400	180	3230	2020	37.5
9-12-80	400	180	2820	2360	16.3
10-27-80	400	180	2960	2510	15.2
					26.0 ± 11.9%
1-28-80	500	180	3260	1220	62.6
2-19-80	500	180	3100	1100	64.5
9-11-80	500	180	2850	1270	55.4
10-17-80	500	180	3320	1570	52.7
					58.8 ± 5.6%
3-17-80	525	110	1018	239	76.5
3-19-80	525	80	613	184	70.0
					73.2 ± 4.6%
3-19-80	550	80	698	296	57.6%
3-14-80	575	110	2035	419	79.4
3-26-80	575	80	528	130	75.4
					77.4 ± 2.8%
1-24-80	600	180	3180	655	79.4
2-14-80	600	180	2800	616	78.0
3-20-80	600	80	668	204	69.5
7-11-80	600	80	469	47	90.0
9-10-80	600	180	2920	870	70.2
10-17-80	600	180	2560	781	69.5
10-25-80	600	180	1740	686	60.6
					73.9 ± 9.4%

TABLE C-8, continued

DATE RUN	REACTION TEMPERATURE ^{0}F	INITIAL PRESSURE psig	TCOD INFLUENT mg/ℓ	TCOD EFFLUENT mg/ℓ	TCOD REDUCTION %
1-22-80	650	180	3080	530	82.9
3-17-80	650	110	2035	377	81.5
3-20-80	650	80	668	165	75.3
3-26-80	650	80	528	71	86.6
4-3-80	650	180	2520	478	81.0
9-9-80	650	180	3100	702	77.4
10-3-80	650	180	2755	677	75.4
10-3-80	650	180	729	178	75.6
10-16-80	650	180	3130	699	77.7
10-16-80	650	180	3474	699	79.9
10-26-80	650	180	1770	360	79.7
					79.4 ± 12.6
3-6-80	680	110	1628	234	85.6
3-19-80	680	80	613	18	97.1
					91.4 ± 8.1

TABLE C-9. LBR RUNS WITH FORTY-FIVE MINUTE REACTION TIMES

DATE RUN	REACTION TEMPERATURE ^0F	INITIAL PRESSURE psig	TCOD INFLUENT mg/ℓ	TCOD EFFLUENT mg/ℓ	TCOD REDUCTION %
4-17-80	450	150	1814	440	75.7%
8-13-80	625	150	399	144	63.9
8-14-80	625	150	386	120	68.9
8-14-80	625	150	386	152	60.6
8-15-80	625	150	448	144	67.8
					65.3 ± 3.8%
2-6-80	650	180	2920	586	79.9
4-10-80	650	150	172	28	83.7
4-14-80	650	150	105	28	73.3
4-17-80	650	150	1900	455	76.0
4-22-80	650	150	543	167	69.2
4-23-80	650	150	490	165	66.3
4-24-80	650	150	521	133	74.5
4-29-80	650	150	1037	328	68.4
4-29-80	650	150	1014	337	66.8
5-1-80	650	150	1500	416	72.7
5-2-80	650	150	1528	356	76.7
5-5-80	650	150	1632	361	77.9
5-5-80	650	150	1632	392	76.0
5-5-80	650	150	1632	360	77.9
11-19-80	650	150	940	297	68.4
					73.8 ± 5.2%

TABLE C-10. LBR RUN DATA WITH THIRTY MINUTE REACTION TIMES

DATE RUN	REACTION TEMPERATURE °F	INITIAL PRESSURE psig	TCOD INFLUENT mg/ℓ	TCOD EFFLUENT mg/ℓ	TCOD REDUCTION %
7-20-79	400	80	450	323	28.2
9-79	400	180	2080	1560	25.0
9-79	400	80	436	314	28.0
9-79	400	80	473	322	32.0
1-30-80	400	180	2880	2310	19.8
3-13-80	400	180	1727	910	47.3
4-1-80	400	180	3230	2360	26.9
9-30-80	400	180	2840	2000	29.6
10-16-80	400	180	3057	2770	9.4
10-24-80	400	180	2980	2350	21.1
					26.7 ± 9.7%
7-19-79	445	NR	420	285	32.1
7-17-80	445	NR	430	209	51.4
7-27-80	445	NR	359	272	24.2
					35.9 ± 14.0%
7-18-79	500	NR	593	262	55.8
9-79	500	NR	2080	998	52.0
9-79	500	NR	436	222	49.0
9-79	500	NR	473	213	55.0
1-29-80	500	180	2960	1370	53.7
2-25-80	500	180	3520	1690	52.0
3-26-80	500	NR	718	384	46.5
7-17-80	500	NR	372	222	40.3
9-11-80	500	180	3200	1780	44.4
10-10-80	500	180	2260	1140	49.6
10-24-80	500	180	2120	1690	20.3
					47.2 ± 10.1%

TABLE C-10, continued

DATE RUN	REACTION TEMPERATURE ^0F	INITIAL PRESSURE psig	TCOD INFLUENT mg/ℓ	TCOD EFFLUENT mg/ℓ	TCOD REDUCTION %
7-18-79	550	NR	484	185	61.8
3-2-80	550	NR	671	343	48.9
					55.4 ± 9.1%
7-13-79	575	NR	460	165	64.1
3-13-80	575	NR	910	284	68.8
3-25-80	575	80	576	278	51.7
3-25-80	575	80	576	264	54.2
					59.7 ± 8.1%
7-11-79	600	NR	469	79	83.2
7-19-79	600	200	533	100	81.2
7-20-79	600	150	549	179	67.9
7-23-79	600	95	823	154	81.3
7-23-79	600	40	597	139	76.7
7-24-79	600	18	523	115	78.0
9-79	600	NR	2080	666	68.0
9-79	600	NR	436	170	61.0
9-79	600	NR	473	142	70.0
1-25-80	600	180	3040	720	76.3
2-18-80	600	180	2810	708	74.8
3-21-80	600	80	671	270	59.8
3-24-80	600	80	661	247	62.6
10-1-80	600	180	2820	1420	49.6
10-8-80	600	180	2840	1060	62.7
10-25-80	600	180	1630	402	75.3
					70.5 ± 9.4%
11-17-80	625	150	940	281	70.1
11-20-80	625	150	940	297	68.4
					69.2 ± 1.2%

TABLE C-10, continued

DATE RUN	REACTION TEMPERATURE ^{0}F	INITIAL PRESSURE psig	TCOD INFLUENT mg/ℓ	TCOD EFFLUENT mg/ℓ	TCOD REDUCTION %
7-13-79	650	NR	460	144	68.7
1-22-80	650	180	3210	591	81.6
2-7-80	650	NR	3000	534	82.2
2-15-80	650	180	2920	576	79.6
3-21-80	650	NR	667	217	67.5
10-2-80	650	180	2860	745	74.0
10-2-80	650	180	2700	807	70.1
10-7-80	650	180	2860	745	74.0
10-8-80	650	180	3160	830	73.7
10-27-80	650	180	2930	405	86.2
					75.8 ± 6.3%

NR - NOT RECORDED

TABLE C-11. LBR RUN DATA WITH TWENTY MINUTE REACTION TIMES

DATE RUN	REACTION TEMPERATURE ^0F	INITIAL PRESSURE psig	TCOD INFLUENT mg/ℓ	TCOD EFFLUENT mg/ℓ	TCOD REDUCTION %
7-25-80	445	80	431	309	28.3
7-29-80	445	80	309	222	28.2
7-30-80	445	80	300	245	18.3
8-1-80	445	80	254	216	15.0
8-8-80	445	80	370	260	29.7
8-8-80	445	80	431	309	28.3
					$\overline{24.6} \pm 6.3\%$
8-1-80	460	80	273	205	24.9%

TABLE C-12. LBR RUN DATA WITH FIFTEEN MINUTE REACTION TIMES

DATE RUN	REACTION TEMPERATURE ^0F	INITIAL PRESSURE psig	TCOD INFLUENT mg/ℓ	TCOD EFFLUENT mg/ℓ	TCOD REDUCTION %
11-26-80	445	80	707	546	22.8
11-26-80	445	80	1000	800	20.0
					21.4 ± 2.0%
7-12-79	600	80	464	120	74.1%

TABLE C-13. LBR SOLIDS DATA FOR DIGESTED SLUDGE, DENVER NORTHSIDE W.W.T.P.

DATE RUN	MAXIMUM TEMPERATURE ^0F	REACTION TIME MINUTES	TS IN mg/ℓ	TS OUT mg/ℓ	TS RDXN %	TVS IN mg/ℓ	TVS OUT mg/ℓ	TVS RDXN %	TSS IN mg/ℓ	TSS OUT mg/ℓ	TSS RDXN %
1-31-80	400	30	3310	2390	28	1870	1120	40	NR	NR	-
1-29-80	500	30	3400	1780	48	1720	568	67	NR	NR	-
1-25-80	600	30	3400	1790	47	1720	232	87	NR	NR	-
1-22-80	650	30	3400	1150	66	1720	90	95	NR	NR	-
1-30-80	400	60	2980	1460	51	1680	680	60	NR	NR	-
1-28-80	500	60	3400	1190	65	1720	284	83	NR	NR	-
1-24-80	600	60	3400	1350	60	1720	188	89	NR	NR	-
1-22-80	650	60	3400	906	73	1720	318	82	NR	NR	-

NR - NOT RUN

TABLE C-14. LBR SOLIDS DATA FOR BLEND OF DIGESTED AND WASTE ACTIVATED SLUDGE, DENVER NORTHSIDE AND DENVER METRO W.W.T.P.

DATE RUN	MAXIMUM TEMPERATURE ^{0}F	REACTION TIME MINUTES	TS IN mg/ℓ	TS OUT mg/ℓ	TS RDXN %	TVS IN mg/ℓ	TVS OUT mg/ℓ	TVS RDXN %	TSS IN mg/ℓ	TSS OUT mg/ℓ	TSS RDXN %
4-1-80	400	30	2940	2220	24	1950	1160	41	NR	NR	-
2-25-80	500	30	3010	1070	64	2170	546	75	NR	NR	-
2-18-80	600	30	2350	654	72	1590	200	87	NR	NR	-
2-15-80	650	30	2340	780	67	1630	140	91	NR	NR	-
4-1-80	400	60	2940	2200	25	1950	1170	40	NR	NR	-
2-19-80	500	60	2940	1370	53	1950	1070	45	NR	NR	-
2-14-80	600	60	2350	700	70	1590	162	90	NR	NR	-
4-3-80	650	60	1820	448	75	1480	112	92	NR	NR	-

NR - NOT RUN

TABLE C-15. LBR SOLIDS DATA FOR PRIMARY SLUDGE, LONGMONT W.W.T.P.

DATE RUN	MAXIMUM TEMPERATURE ^0F	REACTION TIME MINUTES	TS IN mg/ℓ	TS OUT mg/ℓ	TS RDXN %	TVS IN mg/ℓ	TVS OUT mg/ℓ	TVS RDXN %	TSS IN mg/ℓ	TSS OUT mg/ℓ	TSS RDXN %
10-15-80	400	30	2208	NR	-	1370	NR	-	3970	940	76
10-1-80	500	30	2540	NR	-	2070	NR	-	2010	618	69
10-8-80	600	30	2670	NR	-	1790	NR	-	3510	282	92
10-8-80	650	30	2720	NR	-	1670	NR	-	2500	519	79
10-17-80	400	60	1130	NR	-	371	NR	-	1920	820	57
10-17-80	500	60	2330	844	64	1520	274	82	1680	481	71
10-17-80	600	60	2450	936	62	1680	229	86	2080	505	76
10-16-80	650	60	2430	NR	-	1770	NR	-	2210	669	70

NR - NOT RUN

TABLE C-16. LBR SOLIDS DATA FOR PRIMARY SLUDGE WITH FOOD PROCESSING WASTE, BRUSH, W.W.T.P.

DATE RUN	MAXIMUM TEMPERATURE ^{0}F	REACTION TIME MINUTES	TS IN mg/ℓ	TS OUT mg/ℓ	TS RDXN %	TVS IN mg/ℓ	TVS OUT mg/ℓ	TVS RDXN %	TSS IN mg/ℓ	TSS OUT mg/ℓ	TSS RDXN %
10-24-80	400	30	1470	400	73	1050	254	76	689	364	47
10-24-80	500	30	1410	992	30	977	424	57	1250	395	68
10-25-80	600	30	1410	400	72	1050	61	94	NR	121	-
10-27-80	650	30	1930	448	77	1440	139	90	1600	597	63
10-28-80	400	60	1620	NR	-	959	NR	-	1300	NR	-
10-25-80	500	60	2120	709	67	1550	302	81	1140	NR	-
10-25-80	600	60	1380	608	56	1030	186	82	2730	61	98
10-26-80	650	60	1350	522	61	928	116	86	NR	200	-

NR - NOT RUN

TABLE C-17. LBR SOLIDS DATA FOR DOMESTIC WASTE, AURORA W.W.T.P.

DATE RUN	MAXIMUM TEMPERATURE ^{0}F	REACTION TIME MINUTES	TS IN mg/ℓ	TS OUT mg/ℓ	TS RDXN %	TVS IN mg/ℓ	TVS OUT mg/ℓ	TVS RDXN %	TSS IN mg/ℓ	TSS OUT mg/ℓ	TSS RDXN %
9-30-80	400	30	854	NR	-	NR	NR	-	1600	543	66
9-11-80	500	30	1550	1120	28	977	624	36	2000	330	84
10-1-80	600	30	1260	NR	-	1060	NR	-	1900	406	79
10-2-80	650	30	2290	489	79	1720	28	98	2130	50	98
9-12-80	400	60	2570	NR	-	1470	NR	-	1740	1150	34
9-11-80	500	60	2000	581	71	1660	150	91	2580	231	91
9-10-80	600	60	2070	610	71	1562	70	96	2460	203	92
10-3-80	650	60	1990	731	63	1370	140	90	2070	204	90

TABLE C-18. LBR METAL CONCENTRATION DATA FROM SEPTEMBER 1979

DETERMINATION mg/ℓ	600°F*		500°F*	400°F*				
	INFLUENT	EFFLUENT	EFFLUENT	EFFLUENT	INFLUENT	EFFLUENT	EFFLUENT	EFFLUENT
COD	2080	666	998	1560	436	170	222	314
ARSENIC	0.0051	0.0082	0.0016	0.0068	0.0026	0.00054	0.00024	0.00064
CADMIUM	0.011	0.0077	0.0051	0.010	0.0032	0.0018	0.0017	0.0027
CHROMIUM, TOTAL	0.043	0.045	0.034	0.092	0.016	0.057	0.018	0.029
COPPER	0.78	0.51	0.53	0.82	0.41	0.18	0.14	0.25
NICKEL	0.085	0.088	0.06	0.067	0.026	0.042	0.039	0.042
MERCURY	0.00002	0.00003	0.00001	0.00003	0.00013	0.00016	0.00017	0.00021
LEAD	0.32	0.17	0.18	0.25	0.081	0.042	0.039	0.070
IRON	8.03	7.14	11.51	13.8	1.30	1.33	0.86	1.34
MANGANESE	0.85	0.60	0.46	0.79	0.21	0.19	0.14	0.17
ZINC	1.61	1.30	1.02	1.44	0.87	0.39	0.26	0.57

* ALL RUNS ARE FOR 30 MINUTE REACTION TIMES PERFORMED ON UNTREATED SLUDGE FROM ENGLEWOOD W.W.T.P., ENGLEWOOD, COLORADO.

TABLE C-19. LBR METAL CONCENTRATION DATA FROM FEBRUARY 1980

METAL, mg/ℓ	2-7-80*			2-14-80**		
	INFLUENT	EFFLUENT	SOLUBLE EFFLUENT	INFLUENT	EFFLUENT	SOLUBLE EFFLUENT
CADMIUM	0.07	0.05	<0.01	<0.04	0.02	0.06
CHROMIUM, TOTAL	6.7	7.0	3.7	1.5	1.8	1.2
CHROMIUM^{+6}	<0.01	2.46	1.49	<0.01	0.22	0.08
COPPER	2.7	2.5	0.05	0.84	0.70	0.07
NICKEL	0.52	0.51	0.12	0.10	0.12	<0.05
LEAD	5.8	4.2	0.016	1.10	0.83	0.052
ZINC	4.7	4.0	0.04	1.62	1.25	0.16
IRON	33	32	0.19	7.6	10	0.21

* LBR RUN FOR THIRTY MINUTE REACTION TIME AT 650^{o}F PERFORMED ON DIGESTED SLUDGE FROM DENVER NORTHSIDE W.W.T.P., DENVER, COLORADO.

** LBR RUN FOR SIXTY MINUTE REACTION TIME AT 650^{o}F PERFORMED ON DIGESTED SLUDGE FROM DENVER NORTHSIDE W.W.T.P., DENVER, COLORADO.

TABLE C-20. LBR METAL CONCENTRATION DATA FROM OCTOBER 1980

METAL, mg/ℓ	10-16-80*			10-17-80**		
	INFLUENT	EFFLUENT	SOLUBLE EFFLUENT	INFLUENT	EFFLUENT	SOLUBLE EFFLUENT
CHROMIUM, TOTAL	0.12	0.13	0.05	0.11	0.06	0.03
CADMIUM	0.01	<0.01	<0.01	0.01	<0.01	0.01
LEAD	0.331	0.203	<0.005	0.234	0.058	0.007
IRON	9.3	8.8	<0.02	8.2	2.6	0.12
COPPER	2.1	1.3	0.08	1.9	0.48	0.14
NICKEL	0.10	0.07	<0.05	0.09	<0.05	<0.05

* LBR RUN FOR SIXTY MINUTE REACTION TIME AT 650°F PERFORMED ON PRIMARY SLUDGE FROM LONGMONT W.W.T.P., LONGMONT, COLORADO.

** LBR RUN FOR SIXTY MINUTE REACTION TIME AT 600°F PERFORMED ON PRIMARY SLUDGE FROM LONGMONT W.W.T.P., LONGMONT, COLORADO.

TABLE C-21. LBR NITROGEN DATA

DATE RUN	TKN, mg/ℓ IN	TKN, mg/ℓ OUT	mg NH_3-N/ℓ IN	mg NH_3-N/ℓ OUT	mg NO_3^--N/ℓ IN	mg NO_3^--N/ℓ OUT
2-15-80[α]	86	88	NR	92	ND	1.6
10-3-80[β]	200	86	15.0	76	ND	ND
10-16-80[∂]	30	101	6.4	76	ND	ND
10-26-80[Δ]	110	110	5.3	100	ND	ND

NR = NOT RUN

ND = NOT DETECTED

[α] LBR RUN FOR THIRTY MINUTE REACTION TIME AT 650°F ON UNTREATED SLUDGE FROM DENVER NORTHSIDE AND DENVER METRO W.W.T.P., DENVER, COLORADO.

[β] LBR RUN FOR SIXTY MINUTE REACTION TIME AT 650°F ON DOMESTIC WASTE FROM AURORA W.W.T.P., AURORA, COLORADO.

[∂] LBR RUN FOR SIXTY MINUTE REACTION TIME AT 650°F ON PRIMARY SLUDGE FROM LONGMONT W.W.T.P., LONGMONT, COLORADO.

[Δ] LBR RUN FOR SIXTY MINUTE REACTION TIME AT 650°F ON PRIMARY SLUDGE WITH FOOD PROCESSING WASTE FROM BRUSH W.W.T.P., BRUSH, COLORADO.

APPENDIX

PILOT PLANT TEST RESULTS

The following tables present the quantitative results obtained from operation of the pilot plant.

TABLE D-1. SUMMARY OF PILOT PLANT COD REDUCTION DATA

SAMPLING PERIOD	REACTION TEMPERATURE °F	REACTION TIME MINUTES	COD REDUCTION %
OCTOBER 1979	435	17.5	11.9 ± 6.8%
JULY 23, 1980	440	27	38.1%
JULY 24-25, 1980	440	30	29.7 ± 5.5%
AUGUST-SEPTEMBER 1980	394	-	50 ± 22%
NOVEMBER 1980	420	10.6	24.9 ± 8.9%
DECEMBER 1980	433	14	22.0 ± 9.4%
MARCH 19-23, 1981	510	28	42.6 ± 9.4%

TABLE D-2. COD DATA FOR PILOT PLANT FROM OCTOBER 1979

SAMPLE TIME	SAMPLE DATE	REACTION TEMPERATURE °F	REACTION TIME MINUTES	COD, mg/ℓ INFLUENT	COD, mg/ℓ EFFLUENT	% REDUCTION
2300	10-11-79	418	17.5	173	139	19.6%
1000	10-12-79	444	17.5	203	186	8.4%
1400	10-12-79	428	17.5	153	146	4.6%
2359	10-12-79	427	17.5	238	204	14.3%
0300	10-13-79	427	17.5	230	179	22.1%
0600	10-13-79	445	17.5	213	199	6.6%
2200	10-13-79	444	17.5	205	195	4.9%
1400	10-14-79	$\frac{449}{435}$ °F	$\frac{17.5}{17.5}$ MINUES	224	191	$\frac{14.7\%}{11.9 \pm 6.8\%}$

TABLE D-3. COD DATA FOR PILOT PLANT FROM JULY 1980

SAMPE TIME	SAMPLE DATE	REACTION TEMPERATURE °F	REACTION TIME MINUTES	COD, mg/ℓ INFLUENT	COD, mg/ℓ EFFLUENT	% REDUCTION
1000	7-23-80	440	27	118	73	38.1% / 38.1%
1300	7-24-80	440	30	416	292	29.8%
1400	7-24-80	440	30	490	294	40.0%
1500	7-24-80	440	30	398	306	23.1%
1000	7-24-80	440	30	272	195	27.2%
1700	7-24-80	440	30	394	274	30.4%
1800	7-24-80	440	30	370	276	26.4%
1900	7-24-80	440	30	353	268	24.1%
2000	7-24-80	440	30	351	257	28.0%
2100	7-25-80	440	30	361	272	24.6%
2200	7-25-80	440	30	341	247	27.6%
2400	7-25-80	440	30	329	216	34.3%
0200	7-25-80	440	30	288	218	24.3%
0400*	7-25-80	440	30	280	290	-
0600	7-25-80	440	30	286	198	30.8%
0800	7-25-80	440	30	313	200	36.1%

TABLE D-3, continued

SAMPLE TIME	SAMPLE DATE	REACTION TEMPERATURE °F	REACTION TIME MINUTES	COD, mg/ℓ INFLUENT	COD, mg/ℓ EFFLUENT	% REDUCTION
1000	7-25-80	440	30	308	186	39.6
1200*	7-25-80	440	30	290	336	-
1400*	7-25-80	440	30	285	N.R.	-
		440°F	30 MINUTES			29.7 ± 5.5%

* DATA NOT USED TO COMPUTE COD REDUCTION

NR - NOT RECORDED

TABLE D-4. RAW COD DATA FOR PILOT PLANT FROM AUGUST AND NOVEMBER 1980

SAMPLE TIME	SAMPLE DATE	REACTION TEMPERATURE[α] °F	REACTION TIME[β] MINUTES	COD, mg/ℓ INFLUENT	COD, mg/ℓ EFFLUENT	% REDUCTION
2400 G	8-28-80	369		NR	74	-
1327 G	9-4-80	406		74	NR	-
2300 G	9-10-80	402		218	51	77
0300 G	9-11-80	402		74	46	38
2112 G	9-12-80	365		298	21	93
1030 C	9-13-80	382		86	32	63
2200 C	9-13-80	389		78	42	46
0000 C	9-15-80	398		71	24	66
1700 C	9-16-80	413		354	278	21
1620 C	9-17-80	424		6068	4040	33
1545 C	9-18-80	403		52	45	13
0150C	9-19-80	399		24	133	-
0927 C	9-19-80	393		242	146	40
1529 C	9-21-80	376		69	31	55
1530 C	9-22-80	386		33	13	61
2300 C	9-22-80	389		44	25	43
		394°F				50 ± 22%

G - GRAB: C - COMPOSITE: [α]REACTOR BOTTOM IS GENERALLY 100°F HOTTER THAN TC #2 SO THE REACTOR TEMPERATURE WAS GENERATED BY ADDING 100°F TO THE TC #2 TEMPERATURE: [β]NO DATA IS AVAILABLE ON REACTION TIME.

TABLE D-5. RAW COD DATA FOR PILOT PLANT FROM NOVEMBER 1980

SAMPLE TIME	SAMPLE DATE	REACTION TEMPERATURE °F	REACTION TIME MINUTES	COD, mg/ℓ INFLUENT	COD, mg/ℓ EFFLUENT	COD, mg/ℓ % REDUCTION
0500 C	11-6-80	400	6	593	468	21.1%
2300 C	11-6-80	410	7	691	566	18.0%
1415 C	11-7-80	410	7	874	636	27.2%
1515 C	11-8-80	350	0	812	621	23.5%
0445 C	11-12-80	410	10	651	532	18.3%
0600 C	11-19-80	440	14	936	507	45.8%
1445 C	11-19-80	445	15	737	618	16.1%
0930 G	11-20-80	445	17	736	476	35.3%
1430 C	11-20-80	441	14	727	553	23.9%
1000 C	11-21-80	455 420°F	16 10.6 MINUTES	656	524	20.1% 24.9 ± 8.9%

C = COMPOSITE SAMPLE, SAMPLE MADE UP OF 5 REACTOR INFLUENT GRABS TAKEN TEN MINUTES APART STARTING AT THE TIME SHOWN. REACTOR EFFLUENT WAS COMPOSITED OF 5 REACTOR OUT GRABS STARTING APPROXIMATELY 45 MINUTES AFTER THE FIRST REACTOR IN SAMPLE.

G = GRAB

TABLE D-6. RAW COD DATA FOR PILOT PLANT FROM DECEMBER 1980

SAMPLE TIME	SAMPLE DATE	REACTION TEMPERATURE °F	REACTION TIME MINUTES	COD, mg/ℓ		
				INFLUENT	EFFLUENT	% REDUCTION
NR	12-7-80	443	14	656	492	25.0%
1015	12-9-80	443	14	306	200	34.6%
1100	12-9-80	445	14	290	250	13.8%
NR	12-9-80	445	14	318	230	27.7%
1000	12-13-80	437	14	360	272	24.4%
NR	12-13-80	437	14	766	614	19.8%
NR	12-13-80	437	14	908	618	31.9%
NR	12-16-80	437	14	218	127	41.7%
NR	12-16-80	437	14	804	723	10.1%
NR	12-17-80	437	14	483	424	12.2%
0900	12-20-80	427	13	952	588	38.2%

TABLE D-6, continued

SAMPLE TIME	SAMPLE DATE	REACTION TEMPERATURE °F	REACTION TIME MINUTES	COD, mg/ℓ INFLUENT	COD, mg/ℓ EFFLUENT	% REDUCTION
NR	12-20-80	427	13	700	572	18.3%
NR	12-20/80	427	13	684	553	19.2%
NR	12-20-80	427	13	720	608	15.6%
NR	12-20-80	427	13	688	572	16.9%
NR	12-20-80	427	13	673	576	14.4%
1500	12-21-80	431	16	702	580	17.4%
NR	12-21-80	431	16	668	525	21.4%
NR	12-21-80	431	16	621	476	23.3%
NR	12-21-80	431	16	598	537	10.2%
NR	12-21-80	431	16	800	531	33.6%
NR	12-21-80	431	16	608	472	22.4%

TABLE D-6, continued

SAMPLE TIME	SAMPLE DATE	REACTION TEMPERATURE °F	REACTION TIME MINUTES	COD, mg/ℓ INFLUENT	COD, mg/ℓ EFFLUENT	% REDUCTION
NR	12-21-80	431	16	605	500	17.2%
1300	12-22-80	432	14	790	810	-
NR	12-22-80	432	14	765	772	-
NR	12-22-80	432	14	724	784	-
NR	12-22-80	432	14	1029	820	20.3%
NR	12-22-80	432	14	997	818	17.9%
NR	12-22-80	432	14	1170	850	27.4%
NR	12-22-80	432	14	1088	896	17.6%
0900	12-23-80	431	14	1220	866	29.0%
NR	12-23-80	431	14	1240	916	26.1%
NR	12-23-80	431	14	1160	924	20.3%
NR	12-23-80	431	14	1100	912	17.1%
NR	12-23-80	$\frac{431}{433}$	$\frac{14}{14}$ MINUTES	1110	898	$\frac{19.1\%}{22.0 \pm 9.4\%}$

NR - NOT RECORDED

TABLE D-7. RAW COD DATA FOR PILOT PLANT RUNS FROM MARCH 1981

SAMPLE TIME	SAMPLE DATE	REACTION TEMPERATURE °F	REACTION TIME MINUTES	COD, mg/ℓ INFLUENT	COD, mg/ℓ EFFLUENT	% REDUCTION
NR	3-19-81	500	28	1100	574	47.8%
NR	3-19-81	500	28	1120	657	41.3%
NR	3-19-81	500	28	1060	538	49.2%
NR	3-19-81	500	28	1000	586	41.4%
NR	3-19-81	500	28	1030	562	45.4%
NR	3-19-81	500	28	1090	594	45.5%
NR	3-19-81	500	28	1120	714	36.2%
NR	3-20-81	510	28	1080	690	36.1%
NR	3-20-81	510	28	1110	619	44.2%
NR	3-20-81	510	28	1120	643	42.6%
NR	3-20-81	515	28	1150	682	40.7%
NR	3-20-81	515	28	1140	658	42.3%
NR	3-20-81	515	28	1400	792	43.4%
NR	3-21-81	515	28	2380	1200	49.6%
NR	3-21-81	515	28	1560	500	67.9%
1500	3-21-81	515	28	1430	1000	30.1%

TABLE D-7, continued

SAMPLE TIME	SAMPLE DATE	REACTION TEMPERATURE °F	REACTION TIME MINUTES	COD, mg/ℓ INFLUENT	COD, mg/ℓ EFFLUENT	COD, mg/ℓ % REDUCTION
NR	3-21-81	515	28	1290	1030	20.2%
NR	3-21-81	515	28	1610	1080	32.9%
NR	3-21-81	515	28	2490	1180	52.6%
NR	3-21-81	515	28	2230	1130	49.3%
NR	3-21-81	515	28	2020	1230	39.1%
NR	3-22	510	28	1140	681	40.3%
0000	3-23-81	510	28	889	558	37.2%
NR	3-23-81	510	28	961	565	41.2%
NR	3-23-81	510	28	986	598	39.4%
NR	3-23-81	510	28	886	566	36.1%
NR	3-23-81	510	28	1360	580	57.4%
NR	3-23-81	510	28	1120	573	48.8%
1400	3-23-81	510	28	1830	1000	45.4%
NR	3-23-81	510	28	1760	1070	39.2%
NR	3-23-81	510	28	1850	1130	38.9%
NR	3-23-81	510	28	1800	1090	39.4%
NR	3-23-81	510	28	1810	1050	42.0%
		510 °F	28 MINUTES			42.6 ± 9.4%

TABLE D-8. PILOT PLANT BOD DATA FROM JULY 1980[α]

SAMPLE TIME	SAMPLE DATE	BOD, mg/ℓ IN	BOD, mg/ℓ OUT	% REDUCTION
1300	7-24-80	181	148	18
1400	7-24-80	NR	161	-
1500	7-24-80	NR	182	-
1600	7-24-80	NR	177	-
1700	7-24-80	186	156	16
1800	7-24-80	149	NR	-
1900	7-24-80	163	NR	-
2000	7-24-80	184	NR	-
2100	7-24-80	166	161	3
2200	7-24-80	NR	146	-
2400	7-24-80	169	NR	-
0600	7-24-80	NR	220	-
0800[β]	7-24-80	138	158	-
2200	7-24-80	167	NR	-
				$\overline{12} \pm 8\%$

NR - NOT RUN

α - THIRTY MINUTE REACTION TIME AND 440°F REACTION TEMPERATURE

β - COMPUTED WITHOUT DATA FROM THIS DAY

TABLE D-9. PILOT PLANT pH DATA FROM JULY 1980[α]

SAMPLE TIME	SAMPLE DATE	pH IN	pH OUT
1300	7-24-80	7.37	6.71
1400	7-24-80	7.34	6.72
1500	7-24-80	7.24	6.68
1600	7-24-80	7.26	6.73
1700	7-24-80	7.31	6.81
1800	7-24-80	7.32	6.33
1900	7-24-80	7.39	6.40
2000	7-24-80	7.44	6.92
2100	7-24-80	7.49	7.01
2200	7-24-80	7.50	6.86
2400	7-24-80	7.48	7.00
0200	7-25-80	7.15	6.77
0400	7-25-80	7.23	6.73
0600	7-25-80	7.21	6.74
0800	7-25-80	7.22	6.73
1000	7-25-80	7.21	6.67
1200	7-25-80	7.12	6.52
1400	7-25-80	7.06	6.74

α 30 MINUTE REACTION TIME, 440°F REACTION TEMPERATURE

TABLE D-10. VTR PILOT PLANT SOLIDS REMOVAL DATA

SAMPLE DATE	TOTAL SOLIDS mg/ℓ			TOTAL VOL.SOLIDS mg/ℓ			TOTAL SUS.SOLIDS mg/ℓ			TOTAL VOL.SUS.SOLIDS mg/ℓ		
	INF.	EFF.	% REMOVAL	INF.	EFF.	% REMOVAL	INF.	EFF.	% REMOVAL	INF.	EFF.	% REMOVAL
3-19-81[α]	2070	958	54	1140	661	42	1630	488	70	790	452	43
3-20-81[β]	2000	736	64	1040	NR	-	1180	300	75	950	NR	-

[α] 500°F/28 MINUTES

[β] 510°F/28 MINUTES

NR - NOT RUN

TABLE D-11. VTR PILOT PLANT SOLIDS SETTEABILITY DATA*

	TOTAL SOLIDS mg/ℓ	TOTAL VOL. SOLIDS mg/ℓ	TOTAL SUS. SOLIDS mg/ℓ	TOTAL VOL. SUS.SOLIDS mg/ℓ
EFFLUENT	1480	681	600	166
SETTLED EFFLUENT	878	502	141	52
% REMOVED	41	26	74	69

* RESULTS FROM ONE GRAB SAMPLE OF VTR EFFLUENT WHICH WAS PLACED INTO A 2.0 LITER GRADUATED CYLINDER AND ALLOWED TO SETTLE FOR TWO HOURS. THE DECANT FROM THIS CYLINDER WAS THEN POURED OUT CAREFULLY AND ANALYZED FOR SOLIDS DETERMINATION. AN ADDITIONAL 1.0 LITER OF REACTOR EFFLUENT WAS ALSO PLACED INTO A 1.0 LITER IMHOFF CONE. AFTER TWO HOURS THE SETTLED SOLIDS HAD COMPACTED TO 2.5 PERCENT OF THE CONE VOLUME.

TABLE D-12. PILOT PLANT TOTAL SUSPENDED SOLIDS DATA FROM JULY 1980[α]

SAMPLE TIME	SAMPLE DATE	TOTAL SUSPENDED SOLIDS, mg/ℓ		
		IN	OUT	% REDUCTION
1300	7-24-80	128	64	50
1400	7-24-80	396	38	90
1500	7-24-80	373	40	89
1600	7-24-80	164	62	62
1800	7-24-80	112	38	66
1900	7-24-80	88	NR	-
2100	7-24-80	NR	35	-
2200	7-24-80	76	NR	-
0600	7-25-80	NR	77	-
0800	7-25-80	NR	7	-
1200	7-25-80	NR	152	-
1400	7-25-80	92	NR	-
				71 ± 18%

NR - NOT RUN

[α] THIRTY MINUTE REACTION TIME AND 440°F REACTION TEMPERATURE

TABLE D-13. VTR PILOT PLANT METAL CONCENTRATION DATA FROM DECEMBER 1980

METAL, mg/ℓ	12-10-80*			12-15-80*			12-21-80*		
	INFLUENT	EFFLUENT	SOLUBLE EFFLUENT	INFLUENT	EFFLUENT	SOLUBLE EFFLUENT	INFLUENT	EFFLUENT	SOLUBLE EFFLUENT
IRON	6.4	5.6	<0.02	7.9	6.5	<0.02	7.0	6.1	<0.02
CHROMIUM, TOTAL	0.29	0.26	0.03	0.33	0.32	0.03	0.30	0.27	0.03
CHROMIUM, HEXAVALENT	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CADMIUM	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LEAD	0.073	0.061	0.005	0.1030	0.086	0.007	0.091	0.062	0.005
COPPER	0.69	0.60	0.22	0.70	0.56	0.23	0.66	0.56	0.25
NICKEL	0.50	0.05	0.05	0.09	0.05	<0.05	0.10	0.06	<0.05

NR - NOT RUN

* PILOT PLANT CONDITIONS: 433^{o}F REACTION TEMPERATURE AND 14 MINUTE REACTION TIME.

TABLE D-14. VTR PILOT PLANT METAL CONCENTRATION DATA FROM MARCH 1981

	3-19-81*			3-20-81*			3-21-81*		
METAL, mg/ℓ	INFLUENT	EFFLUENT	SOLUBLE EFFLUENT	INFLUENT	EFFLUENT	SOLUBLE EFFLUENT	INFLUENT	EFFLUENT	SOLUBLE EFFLUENT
CALCIUM	130	33	25	120	27	13	170	42	19
COPPER	1.7	0.90	0.65	1.3	0.68	0.35	2.1	1.6	0.84
CHROMIUM, TOTAL	0.35	0.28	0.14	0.28	0.20	0.08	0.36	0.30	0.09
CHROMIUM, HEXAVALENT	NR	<0.01	NR	NR	<0.01	NR	NR	<0.01	NR
LEAD	0.285	0.190	0.128	0.220	0.134	0.037	0.370	0.240	0.092
MAGNESIUM	20	20	15	20	15	8.6	25	22	10
NICKEL	0.10	<0.05	<0.05	0.10	<0.05	<0.05	0.12	0.09	0.06
ZINC	2.24	2.08	1.40	1.82	1.38	0.51	2.35	2.07	0.83
IRON	1.0	0.81	3.8	0.79	0.52	1.8	1.3	1.1	3.0

NR - NOT RUN

* PILOT PLANT CONDITIONS: AVERAGE 510°F REACTION TEMPERATURE AND 28 MINUTE REACTION TIME

TABLE D-15. VTR PILOT PLANT DATA FROM MARCH 1981

PARAMETER, mg/ℓ	3-19-81*		3-20-81*		3-21-81*	
	INFLUENT	EFFLUENT	INFLUENT	EFFLUENT	INFLUENT	EFFLUENT
HARDNESS	233	180	420	170	460	240
TKN	119	117	100	102	142	146
NITRATE (AS N)	0.06	0.36	<0.05	0.04	<0.05	0.36
AMMONIA (AS N)	74	96	56	76	90	140
TOTAL PHOSPHORUS	80	60	67	43	95	73
ORTHOPHOSPHORUS	65	47	64	29	71	74

* PILOT PLANT CONDITIONS: 509°F REACTION TEMPERATURE AND 28 MINUTES REACTION TIME

TABLE D-16. PILOT PLANT NITROGEN DATA FOR JULY 1980*

SAMPLE TIME	SAMPLE DATE	mg NH_3- N/ℓ			TKN, mg/ℓ		
		IN	OUT	% CHANGE	IN	OUT	% CHANGE
1300	7-24-80	46	47	102	45	45	0
1400	7-24-80	38	42	110	42	41	-3
1500	7-24-80	39	40	103	41	41	0
1600	7-24-80	36	37	103	40	37	-8
1700	7-24-80	34	38	112	39	36	-8
1800	7-24-80	36	37	103	39	35	-10
2100	7-24-80	36	37	103	35	34	+3
2200	7-24-80	36	NR	-	34	NR	-
0700	7-25-80	NR	38	-	NR	34	-
0800	7-25-80	37	NR	-	34	NR	-
1300	7-25-80	NR	36	-	NR	34	-
1400	7-25-80	37	NR	-	34	NR	-

* PILOT PLANT CONDITIONS: 440°F REACTION TEMPERATURE AND 30 MINUTE REACTION TIME

APPENDIX E

PILOT PLANT - COMPUTER MODEL

CORRELATION DATA

Two sets of data are shown for each date listed. The first line lists the values that were measured at the pilot plant. The second line lists the values that were used in the computer simulation. In some cases thermocouple readings were not available at depths needed by the computer model. In these cases the measured values have been extrapolated or interpolated. The measured pressures are all in units of psi gauge and the computer values are in psi absolute. The difference in Denver, Colorado, is 12.2 psi.

The three columns between the double bars are the quantities that are correlated in the text. During the month of November, 1980, the air was injected at surface. At all other times the air was injected at a depth of 140 feet.

TABLE E-1. PPR DATA AND COMPUTER SIMULATION DATA LISTED BY DATE

DATE	THERMOCOUPLES (°F) 1	2	4	5	6	IN	OUT	LIQUID FLOW (GPM)	AIR FLOW (LB/HR)	PRESSURES DOWN HOLE (PSIG/PSIA) IN	OUT	ΔT (°F)	DATA SETS AVERAGED
8-19-80		82.3				67.3	67.2	4.0	0	20.0	582	9.0 -0.1	2
	86.2		73.5			67.3	67.2	4.0	0	32.2	584	20.1 0.6	
8-19-80		81.6	68.4			67.7	68.2	3.1	0	16.0	582	8.0 0.5	2
	87.5		68.4			67.7	68.2	3.1	0	28.2	584	21.1 0.1	
8-19-80		81.6	68.4			67.7	68.2	8.2	0	69.0	600	10.0 0.5	1
	87.5		68.4			67.7	68.2	8.2	0	81.2	605	31.0 0.1	
8-19-80		80.5	69.5			67.3	68.2	6.0	0	36.0	597	8.0 0.9	2
	85.4		69.5			67.3	68.2	6.0	0	48.2	590	21.2 0.2	
8-19-80		80.1	69.5			67.3	68.4	7.0	0	52.0	600	10.0 1.1	2
	84.8		69.5			67.3	68.4	7.0	0	64.2	598	27.5 0.2	
8-19-80		79.2	69.9			67.6	68.6	7.0	2.91	57.0	591	12.0 1.0	2
	83.3		69.9			67.6	68.6	7.0	2.91	69.2	577	17.2 0.2	
8-19-80		79.0	70.4			68.0	69.0	6.9	6.12	60.0	572	13.0 1.0	2
	82.8		70.4			68.0	69.0	6.9	6.12	72.2	549	17.4 0.2	
8-19-80		78.6	70.4			68.4	69.2	6.9	10.27	78.0	562	14.0 0.8	7
	82.3		70.4			68.4	69.2	6.9	10.27	90.2	538	29.7 0.2	
8-20-80		81.1	68.7	65.6	63.7	66.1	66.4	5.9	2.79	46.0	588	11.0 0.3	2
	86.6		68.7			66.1	66.4	5.9	2.79	58.2	564	10.6 0.2	
8-20-80		80.3	69.3	67.0	64.9	66.4	66.8	5.9	6.21	66.0	570	12.0 0.4	1
	85.2		69.3			66.4	66.8	5.9	6.21	78.2	550	22.7 0.3	
8-20-80		80.2	69.5	67.2	65.1	66.4	66.7	5.9	10.58	90.0	570	13.0 0.3	
	85.0		69.5			66.4	66.7	5.9	10.58	102.2	542	39.4 0.3	3

TABLE E-1., continued

DATE	THERMOCOUPLES (°F) 1	2	4	5	6	IN	OUT	LIQUID FLOW (GPM)	AIR FLOW (LB/HR)	PRESSURES IN	DOWN HOLE (PSIG/PSIA)	OUT	ΔT (°F)	DATA SETS AVERAGED
8-20-80		79.8	70.0	67.4	65.4	66.9	67.5	5.1	2.83	41.0	567	12.0	0.6	7
	84.2		70.0			66.9	67.5	5.1	2.83	53.2	551	6.2	0.2	
8-20-80		79.6	69.9	67.4	65.5	67.1	67.5	5.1	6.26	90.0	581	11.0	0.4	3
	83.9		69.9			67.1	67.5	5.1	6.26	102.2	569	40.0	0.3	
8-20-80		79.6	70.2	67.8	65.9	67.5	67.8	5.1	5.84	100.0	570	11.0	0.3	1
	83.8		70.2			67.5	67.8	5.1	5.84	112.2	586	49.5	0.2	
8-20-80		79.6	70.2	67.8	66.2	67.4	67.5	4.0	2.04	83.0	577	12.0	0.1	3
	83.8		70.2			67.4	67.5	4.0	2.04	95.2	593	35.5	0.3	
8-20-80		79.9	70.4	68.0	66.5	67.5	67.6	4.0	1.41	73.0	578	12.0	0.1	4
	84.1		70.4			67.5	67.6	4.0	1.41	85.2	593	29.4	0.3	
8-20-80		79.5	70.6	68.0	66.4	67.4	67.3	4.0	0.79	34.0	585	12.0	-0.1	3
	83.5		70.6			67.4	67.3	4.0	0.79	46.2	563	-	-	
11-2-80		91.2	77.2	69.3	59.4	53.4	53.3	7.1	0	90.0	-	10.0	-0.1	1
	97.4		77.2			53.4		7.1	0	102.2	634	64.4	2.6	
11-2-80		88.6	76.2	66.2	57.5	50.8	52.6	4.6	3.39	143.0	-	60.0	1.8	3
	94.1		76.2			50.8	52.6	4.6	3.39	155.2	632	79.0	2.1	
11-2-80		93.1	87.3	83.4	66.7	52.7	56.5	2.3	0	408.0	-	382.0	3.8	6
	95.7		87.3			52.7	56.5	2.3	0	420.2	976	418.0	2.8	
11-2-80		93.1	87.3	83.4	66.7	52.7	56.5	4.4	2.69	412.0	-	253.0	-	4
	95.7		87.3			52.7	56.5	4.4	2.69	424.2	929	368.0	3.1	

TABLE E-1., continued

DATE	THERMOCOUPLES (°F) 1	2	4	5	6	IN	OUT	LIQUID FLOW (GPM)	AIR FLOW (LB/HR)	PRESSURES IN	DOWN HOLE	OUT	ΔT (°F)	DATA SETS AVERAGED
										(PSIG/PSIA)				
11-5-80		275	238	148	99	53.0	61.9	4.4	3.99	156	-	70	8.9	4
	291		238			53.0	61.9	4.4	3.99	168	587	87	14.5	
11-5-80		310	250	158	106	57.1	67.3	4.0	2.03	151	-	82	10.2	2
	337		250			57.1	67.3	4.0	2.03	163	599	90	15.4	
11-5-80		312	252	162	111	58.3	69.8	4.6	2.44	150	-	80	11.5	2
	339		252			58.3	69.8	4.6	2.44	162	605	98	16.4	
11-6-80		325	262	168	112	57.1	68.0	4.5	4.29	148	-	56	10.9	4
	353		262			57.1	68.0	4.5	4.29	160	567	78	15.9	
11-6,7-80		342	271	175	113	57.3	69.5	4.6	4.31	145	-	53	12.2	3
	374		271			57.3	69.5	4.6	4.31	157	563	77	16.8	
11-7-80		344	271	177	112	58.1	71.0	4.6	4.20	148	-	55	12.9	3
	377		271			58.1	71.0	4.6	4.20	160	568	81	16.8	
11-8-80		296	244	162	102	57.8	69.9	4.6	3.40	130	-	55	12.1	2
	319		244			57.8	69.9	4.6	3.40	142	567	68	14.9	
11-11-80		282	207	141	99	53.4	66.0	3.0	0	103	-	47	11.6	3
	315		207			53.4	66.0	3.0	0	115	635	114	13.4	
11-11-80		256	226	146	98	54.0	70.1	3.0	0	76	-	44	16.1	2
	269		226			54.0	70.1	3.0	0	88	608	87.9	15.1	
11-12-80		286	264	166	106	55.5	67.6	4.4	3.83	150	-	56	12.1	6
	296		264			55.5	67.6	4.4	3.83	162	578	82	16.3	
11-12-80		322	258	171	108	56.9	69.7	4.6	3.28	146	-	47	12.8	3
	351		258			56.9	69.7	4.6	3.28	158	584	86	16.4	

TABLE E-1., continued

DATE	THERMOCOUPLES (°F) 1	2	4	5	6	IN	OUT	LIQUID FLOW (GPM)	AIR FLOW (LB/HR)	PRESSURES IN	DOWN HOLE	OUT	ΔT (°F)	DATA SETS AVERAGED
8-24-80		291	216	147	111	70.0	85.0	4.0	1.20	59	615	53	15.0	4
	324		216			70.0	85.0	4.0	1.20	71	538	23.8	13.2	
8-24-80		312	233	160	118	75.8	91.4	5.1	0	67	-	54	15.6	2
	347		233			75.8	91.4	5.1	0	79	583	68	15.7	
8-26-80		294	207	147	123	78.0	91.2	3.1	0	61	-	59	13.2	13
	333		207			78.0	91.2	3.1	0	73	590	72	11.4	
8-26-80		244	223	168	127	80.3	90.2	4.6	3.28	95	569	53	9.9	2
	253		223			80.3	90.2	4.6	3.28	107	248	52	13.2	
8-27-80		245	212	154	122	82.1	94.7	4.4	0	35	560	25	12.6	10
	260		212			82.1	94.7	4.4	0	47	563	38	12.5	
8-28,29-80		276	234	156	111	71.9	82.6	4.0	2.23	82	605	50	10.7	15
	295		234			71.9	82.6	4.0	2.23	94	542	37	14.5	
8-31-80		295	233	159	112	76.8	86.0	4.1	2.62	77	630	51	9.2	5
	323		233			76.8	86.0	4.1	2.62	89	530	31	13.8	
8-31-80		294	233	163	106	69.5	79.8	4.0	2.69	92	635	61	10.3	3
	321		233			69.5	79.8	4.0	2.69	104	544	44	14.6	
9-1-80		297	238	165	103	62.7	74.3	4.1	2.16	93	620	65	11.6	5
	323		238			62.7	74.3	4.1	2.16	105	556	50	16.0	
9-3-80		304	245	170	106	69.0	80.4	4.3	1.96	90	-	54	11.4	8
	330		245			69.0	80.4	4.3	1.96	102	558	51	16.3	
9-4,5-80		306	248	169	101	66.6	78.4	4.1	1.87	87	-	53	11.8	8
	332		248			66.6	78.4	4.1	1.87	99	552	46	16.6	

TABLE E-1., continued

DATE	THERMOCOUPLES (°F) 1	2	4	5	6	IN	OUT	LIQUID FLOW (GPM)	AIR FLOW (LB/HR)	PRESSURES IN	DOWN HOLE (PSIG/PSIA)	OUT	ΔT (°F)	DATA SETS AVERAGED
9-10-80		303	231	161		63.8	76.5	3.9	0	77	300	50	12.7	5
	335		231			63.8	76.5	3.9	0	89	600	84	15.6	
9-11-80		303	233	163	104	61.4	75.1	4.0	0	74	300	50	13.7	9
	334		233			61.4	75.1	4.0	0	86	597	81	16.1	
9-12-80		266	214	150	100	59.5	72.7	4.1	0	71	-	54	13.2	4
	289		214			59.5	72.7	4.1	0	83	599	77	14.6	
9-13-80		281	225	160	104	60.0	75.1	4.2	0	72	280	53	15.1	15
	306		225			60.0	75.1	4.2	0	84	597	78	15.7	